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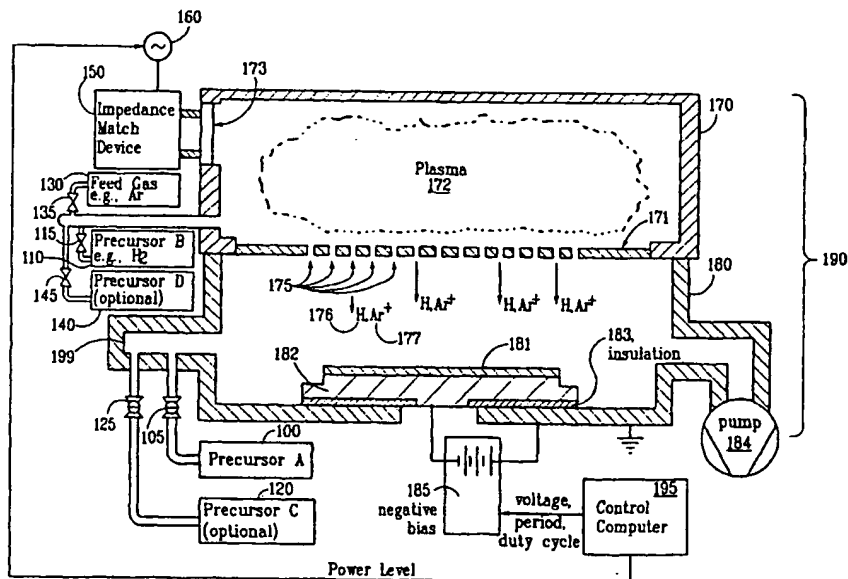
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- (54) Title:** SYSTEM AND METHOD FOR MODULATED ION-INDUCED ATOMIC LAYER DEPOSITION (MII-ALD)



- (57) Abstract:** The present invention relates to an enhanced sequential or non-sequential atomic layer deposition (ALD) apparatus and technique suitable for deposition of barrier layers, adhesion layers, seed layers, low dielectric constant (low-k) films, high dielectric constant (high-k) films, and other conductive, semi-conductive, and non-conductive films. This is accomplished by providing a non-thermal or non-pyrolytic means of triggering the deposition reaction; providing a means of depositing a purer film of higher density at lower temperatures; providing a means of modulating the deposition sequence and hence the overall process rate; and providing a means of improved radical (176) generation and delivery.



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Specification

1 Cross-Reference to Related Applications

2 This application claims the benefit of U.S. Provisional Application Nos.
3 60/251,795, and 60/254,280, both filed December 6, 2000, as well as U.S.
4 Utility Application Nos. 09/812, 285, 09/812,352, and 09/812,486, all filed
5 March 19, 2001, and U.S. Utility Application No. 09/854,092, filed May 10,
6 2001.

7 Background of the Invention

8 The present invention relates generally to the field of advanced thin
9 film deposition methods commonly used in the semiconductor, data storage,
10 flat panel display, as well as allied or other industries. More particularly, the
11 present invention relates to an enhanced sequential or non-sequential atomic
12 layer deposition (ALD) apparatus and technique suitable for deposition of
13 barrier layers, adhesion layers, seed layers, low dielectric constant (low-k)
14 films, high dielectric constant (high-k) films, and other conductive, semi-
15 conductive, and non-conductive thin films.

16 The disadvantages of conventional ALD are additionally discussed in a
17 copending application with the same assignee entitled "Method and
18 Apparatus for Improved Temperature Control in Atomic Layer Deposition",
19 which is hereby incorporated by reference in its entirety and may be found as
20 copending provisional, Application No. 09/854,092.

1 **Brief Description of the Prior Art**

2 As integrated circuit (IC) dimensions shrink and the aspect ratios of the
3 resulting features increase, the ability to deposit conformal, ultra-thin films on
4 the sides and bottoms of high aspect ratio trenches and vias becomes
5 increasingly important. These conformal, ultra-thin films are typically used
6 as "liner" material to enhance adhesion, prevent inter-diffusion and/or
7 chemical reaction between the underlying dielectric and the overlying metal,
8 and promote the deposition of a subsequent film.

9 In addition, decreasing device dimensions and increasing device
10 densities has necessitated the transition from traditional CVD tungsten plug
11 and aluminum interconnect technology to copper interconnect technology.
12 This transition is driven by both the increasing impact of the RC interconnect
13 delay on device speed and by the electromigration (i.e., the mass transport of
14 metal due to momentum transfer between conducting electrons and diffusing
15 metal atoms, thereby affecting reliability) limitations of aluminum based
16 conductors for sub 0.25 μm device generations. Copper is preferred due to its
17 lower resistivity and higher (greater than 10 times) electromigration resistance
18 as compared to aluminum. A single or dual damascene copper metallization
19 scheme is used since it eliminates the need for copper etching and reduces the
20 number of integration steps required. However, the burden now shifts to the
21 metal deposition step(s) as the copper must fill predefined high aspect ratio
22 trenches and/or vias in the dielectric. Electroplating has emerged as the
23 copper fill technique of choice due to its low deposition temperature, high
24 deposition rate, and potential low manufacturing cost.

1 Two major challenges exist for copper wiring technology: the barrier
2 and seed layers. Copper can diffuse readily into silicon and most dielectrics.
3 This diffusion may lead to electrical leakage between metal wires and poor
4 device performance. An encapsulating barrier layer is needed to isolate the
5 copper from the surrounding material (e.g., dielectric or Si), thus preventing
6 copper diffusion into and/or reaction with the underlying material (e.g.
7 dielectric or Si). In addition, the barrier layer also serves as the adhesion or
8 glue layer between the patterned dielectric trench or via and the copper used
9 to fill it. The dielectric material can be a low dielectric constant, i.e. low-k
10 material (used to reduce inter- and intra-line capacitance and cross-talk)
11 which typically suffers from poorer adhesion characteristics and lower
12 thermal stability than traditional oxide insulators. Consequently, this places
13 more stringent requirements on the barrier material and deposition method.
14 An inferior adhesion layer will, for example, lead to delamination at either the
15 barrier-to-dielectric or barrier-to-copper interfaces during any subsequent
16 anneal and/or chemical mechanical planarization (CMP) processing steps
17 leading to degradation in device performance and reliability. Ideally, the
18 barrier layer should be thin, conformal, defect free, and of low resistivity so as
19 to not compromise the conductance of the copper metal interconnect
20 structure.

21 In addition, electroplating fill requires a copper seed layer, which
22 serves to both carry the plating current and act as the nucleation layer. The
23 preferred seed layer should be smooth, continuous, of high purity, and have
24 good step coverage with low overhang. A discontinuity in the seed layer will

1 lead to sidewall voiding, while gross overhang will lead to pinch-off and the
2 formation of top voids.

3 Both the barrier and seed layers which are critical to successful
4 implementation of copper interconnects require a means of depositing high
5 purity, conformal, ultra-thin films at low substrate temperatures.

6 Physical vapor deposition (PVD) or sputtering has been adopted as the
7 preferred method of choice for depositing conductor films used in IC
8 manufacturing. This choice has been primarily driven by the low cost, simple
9 sputtering approach whereby relatively pure elemental or compound
10 materials can be deposited at relatively low substrate temperatures. For
11 example, refractory based metals and metal compounds such as tantalum
12 (Ta), tantalum nitride (TaN_x), other tantalum containing compounds, tungsten
13 (W), tungsten nitride (WN_x), and other tungsten containing compounds which
14 are used as barrier/adhesion layers can be sputter deposited with the
15 substrate at or near room temperature. However, as device geometries have
16 decreased, the step coverage limitations of PVD have increasingly become an
17 issue since it is inherently a line-of-sight process. This limits the total number
18 of atoms or molecules which can be delivered into the patterned trench or via.
19 As a result, PVD is unable to deposit thin continuous films of adequate
20 thickness to coat the sides and bottoms of high aspect ratio trenches and vias.
21 Moreover, medium/high-density plasma and ionized PVD sources developed
22 to address the more aggressive device structures are still not adequate and are
23 now of such complexity that cost and reliability have become serious
24 concerns.

1 Chemical vapor deposition (CVD) processes offer improved step
2 coverage since CVD processes can be tailored to provide conformal films.
3 Conformality ensures the deposited films match the shape of the underlying
4 substrate, and the film thickness inside the feature is uniform and equivalent
5 to the thickness outside the feature. Unfortunately, CVD requires
6 comparatively high deposition temperatures, suffers from high impurity
7 concentrations, which impact film integrity, and have higher cost-of-
8 ownership due to long nucleation times and poor precursor gas utilization
9 efficiency. Following the tantalum containing barrier example, CVD Ta and
10 TaN films require substrate temperatures ranging from 500 °C to over 800 °C
11 and suffer from impurity concentrations (typically of carbon and oxygen)
12 ranging from several to tens of atomic % concentration. This generally leads
13 to high film resistivities (up to several orders of magnitude higher than PVD),
14 and other degradation in film performance. These deposition temperatures
15 and impurity concentrations make CVD Ta and TaN unusable for IC
16 manufacturing, in particular for copper metallization and low-k integration.

17 Chen et al. ("Low temperature plasma-assisted chemical vapor
18 deposition of tantalum nitride from tantalum pentabromide for copper
19 metallization", J. Vac. Sci. Technol. B 17(1), pp. 182-185 (1999); and "Low
20 temperature plasma-promoted chemical vapor deposition of tantalum from
21 tantalum pentabromide for copper metallization", J. Vac. Sci. Technol. B 16(5),
22 pp. 2887-2890 (1998)) have demonstrated a plasma-assisted (PACVD) or
23 plasma-enhanced (PECVD) CVD approach using tantalum pentabromide
24 (TaBr₅) as the precursor gas to reduce the deposition temperature. Ta and

1 TaN_x films were deposited from 350 °C to 450 °C and contained 2.5 to 3
2 atomic % concentration of bromine. Although the deposition temperature has
3 been reduced by increased fragmentation (and hence increased reactivity) of
4 the precursor gases in the gas-phase via a plasma, the same fragmentation
5 leads to the deposition of unwanted impurities. Gas-phase fragmentation of
6 the precursor into both desired and undesired species inherently limits the
7 efficacy of this approach.

8 Recently, atomic layer chemical vapor deposition (AL-CVD) or atomic
9 layer deposition (ALD) has been proposed as an alternative method to CVD
10 for depositing conformal, ultra-thin films at comparatively lower
11 temperatures. ALD is similar to CVD except that the substrate is sequentially
12 exposed to one reactant at a time. Conceptually, it is a simple process: a first
13 reactant is introduced onto a heated substrate whereby it forms a monolayer
14 on the surface of the substrate. Excess reactant is pumped out. Next a second
15 reactant is introduced and reacts with the first reactant to form a monolayer of
16 the desired film via a self-limiting surface reaction. The process is self-
17 limiting since the deposition reaction halts once the initially adsorbed (physi-
18 or chemi-sorbed) monolayer of the first reactant has fully reacted with the
19 second reactant. Finally, the excess second reactant is evacuated. The above
20 sequence of events comprises one deposition cycle. The desired film
21 thickness is obtained by repeating the deposition cycle the required number
22 of times.

23 In practice, ALD is complicated by the painstaking selection of a
24 process temperature setpoint wherein both: 1) at least one of the reactants

1 sufficiently adsorbs to a monolayer and 2) the surface deposition reaction can
2 occur with adequate growth rate and film purity. If the substrate temperature
3 needed for the deposition reaction is too high, desorption or decomposition of
4 the first adsorbed reactant occurs, thereby eliminating the layer-by-layer
5 process. If the temperature is too low, the deposition reaction may be
6 incomplete (i.e., very slow), not occur at all, or lead to poor film quality (e.g.,
7 high resistivity and/or high impurity content). Since the ALD process is
8 entirely thermal, selection of available precursors (i.e., reactants) that fit the
9 temperature window becomes difficult and sometimes unattainable. Due to
10 the above-mentioned temperature related problems, ALD has been typically
11 limited to the deposition of semiconductors and insulators as opposed to
12 metals. ALD of metals has been confined to the use of metal halide
13 precursors. However, halides (e.g., Cl, F, Br) are corrosive and can create
14 reliability issues in metal interconnects.

15 Continuing with the TaN example, ALD of TaN films is confined to a
16 narrow temperature window of 400 °C to 500 °C, generally occurs with a
17 maximum deposition rate of 0.2 Å/cycle, and can contain up to several
18 atomic percent of impurities including chlorine and oxygen. Chlorine is a
19 corrosive, can attack copper, and lead to reliability concerns. The above
20 process is unsuitable for copper metallization and low-k integration due to
21 the high deposition temperature, slow deposition rate, and chlorine impurity
22 incorporation.

23 In conventional ALD of metal films, gaseous hydrogen (H_2) or
24 elemental zinc (Zn) is often cited as the second reactant. These reactants are

1 chosen since they act as a reducing agent to bring the metal atom contained in
2 the first reactant to the desired oxidation state in order to deposit the end film.
3 Gaseous, diatomic hydrogen (H_2) is an inefficient reducing agent due to its
4 chemical stability, and elemental zinc has low volatility (e.g., it is very
5 difficult to deliver sufficient amounts of Zn vapor to the substrate) and is
6 generally incompatible with IC manufacturing. Unfortunately, due to the
7 temperature conflicts that plague the ALD method and lack of kinetically
8 favorable second reactant, serious compromises in process performance
9 result.

10 In order to address the limitations of traditional thermal or pyrolytic
11 ALD, radical enhanced atomic layer deposition (REALD, US Patent 5,916,365)
12 or plasma-enhanced atomic layer deposition has been proposed whereby a
13 downstream radio-frequency (RF) glow discharge is used to dissociate the
14 second reactant to form more reactive radical species which drives the
15 reaction at lower substrate temperatures. Using such a technique, Ta ALD
16 films have been deposited at 0.16 to 0.5 Å/cycle at 25 °C, and up to
17 approximately 1.67 Å/cycle at 250 °C to 450 °C. Although REALD results in a
18 lower operating substrate temperature than all the aforementioned
19 techniques, the process still suffers from several significant drawbacks.
20 Higher temperatures must still be used to generate appreciable deposition
21 rates. Such temperatures are still too high for some films of significant
22 interest in IC manufacturing such as polymer-based low-k dielectrics that are
23 stable up to temperatures of only 200 °C or less. REALD remains a thermal or
24 pyrolytic process similar to ALD and even CVD since the substrate

1 temperature provides the required activation energy for the process and is
2 therefore the primary control means for driving the deposition reaction.

3 In addition, Ta films deposited using REALD still contain chlorine as
4 well as oxygen impurities, and are of low density. A low density or porous
5 film leads to a poor barrier against copper diffusion since copper atoms and
6 ions have more pathways to traverse the barrier material. Moreover, a porous
7 or under-dense film has lower chemical stability and can react undesirably
8 with overlying or underlying films, or with exposure to gases commonly used
9 in IC manufacturing processes.

10 Another limitation of REALD is that the radical generation and
11 delivery is inefficient and undesirable. RF plasma generation of radicals used
12 as the second reactant such as atomic H is not as efficient as microwave
13 plasma due to the enhanced efficiency of microwave energy transfer to
14 electrons used to sustain and dissociate reactants introduced in the plasma.
15 Furthermore, having a downstream configuration whereby the radical
16 generating plasma is contained in a separate vessel located remotely from the
17 main chamber where the substrate is situated and using a small aperture to
18 introduce the radicals from the remote plasma vessel to the main chamber
19 body significantly decreases the efficiency of transport of the second radical
20 reactant. Both gas-phase and wall recombination will reduce the flux of
21 desired radicals that can reach the substrate. In the case of atomic H, these
22 recombination pathways will lead to the formation of diatomic H₂, a far less
23 effective reducing agent. If the plasma used to generate the radicals was

1 placed directly over the substrate, then the deposition of unwanted impurities
2 and particles can occur similarly to the case of plasma-assisted CVD.

3 Finally, ALD (or any derivative such as REALD) is fundamentally slow
4 since it relies on a sequential process whereby each deposition cycle is
5 comprised of at least two separate reactant flow and evacuation steps, which
6 can occur on the order of minutes with conventional valve and chamber
7 technology. Significant improvements resulting in faster ALD are needed to
8 make it more suitable for commercial IC manufacturing.

1 **Brief Description of The Drawings**

2 Figure 1 is a schematic of a deposition system suitable for modulated
3 ion-induced atomic layer deposition (MII-ALD).

4 Figure 2A depicts a timing sequence for an improved ALD method
5 incorporating periodic exposure of the substrate to ions.

6 Figure 2B is another timing sequence for an improved ALD method
7 incorporating periodic exposure of the substrate to ions.

8 Figure 3A shows the MII-ALD method utilizing ion flux modulation to
9 vary the substrate exposure to ions.

10 Figure 3B shows the timing of the MII-ALD method utilizing ion
11 energy modulation to vary the substrate exposure to ions by varying the
12 substrate bias.

13 Figures 4A-F show methods of modulating the MII-ALD process.

14 Figure 5 shows an electrostatic chuck (ESC) system suitable for
15 modulating the ion energy in the MII-ALD process: a) in topological form;
16 and, b) as an equivalent electrical circuit.

17

1 Summary and Detailed Description of the Invention

2 The present invention relates to methods and apparatuses useable for
3 the deposition of conformal solid thin films of one or more elements at low
4 temperature. More particularly, the present invention relates to an enhanced
5 sequential or, more preferably, non-sequential atomic layer deposition
6 apparatus and technique suitable for deposition of barrier layers, adhesion
7 layers, seed layers, and low dielectric constant (low-k) films, high dielectric
8 constant (high-k) films, and other conductive, semi-conductive, and non-
9 conductive thin films.

10 More specifically, the present invention resolves the previously
11 presented problems encountered in the prior art (e.g., REALD) by 1)
12 providing a non-thermal or non-pyrolytic means of triggering the deposition
13 reaction; 2) providing a means of depositing a purer film of higher density at
14 lower temperatures; 3) providing a faster and more efficient means of
15 modulating the deposition sequence and hence the overall process rate
16 resulting in an improved deposition method; and, 4) providing a means of
17 improved radical generation and delivery.

18 Improvements to ALD processing, e.g., the REALD mentioned
19 previously, remain "thermal" or "pyrolytic" processes since the substrate
20 temperature provides the required activation energy and is the primary
21 control knob for driving the deposition reaction. Alternatively, we propose a
22 novel approach by providing the required activation energy from a "non-
23 thermal" source. In particular, we propose driving the deposition reaction
24 primarily via substrate exposure to impinging ions wherein the ions are used

1 to deliver the necessary activation energy to the near surface atoms and
2 adsorbed reactant(s) via collision cascades.

3 Conventional deposition processes used in the semiconductor industry
4 (including ALD) typically deposit materials at temperatures in the range of
5 300-600 °C. The deposition method described herein can be effected at much
6 lower temperatures, in practice as low as 25 °C or below. Note that this
7 process is ion-triggered (i.e., ion-induced) as opposed to ion-assisted in that
8 deposition will not generally occur without ion bombardment since ions are
9 used as the primary means of providing the activation energy required for
10 deposition. A primary benefit of ion-induced processing is the deposition of
11 higher density films of superior purity and adhesion properties. This result
12 occurs due to ion bombardment induced densification.

13 Figure 1 illustrates a deposition system suitable for modulated ion-
14 induced atomic layer deposition (MII-ALD). The invention described herein
15 also incorporates a means of modulating the exposure of the substrate to ions.
16 By modulating 1) the ion flux; 2) the energy of the ions striking the substrate;
17 or a combination of (1) and (2), the deposition reaction can be precisely
18 toggled "on" or "off". If the ion flux or energy is at a "low" state, then no
19 deposition results or deposition occurs so slowly that essentially no
20 deposition results. If the impinging ion flux or energy is at a "high" state,
21 then deposition occurs. Since the substrate (which may be a "bare" substrate,
22 e.g., a silicon wafer before any films have been deposited, or it may be a
23 substrate which may already have had one or more films deposited on its
24 surface) 181 is preferably maintained at a low substrate temperature, the first

1 and second reactants do not thermally react with any appreciable rate or do
2 not react at all. Instead, the deposition reaction only takes place when either
3 the ion flux or ion energy is toggled to a suitable "high state". The desired
4 film thickness is built up by repeating the ion pulses (either of flux or energy)
5 the required number of cycles. Furthermore, since modulation of the ion flux
6 or ion energy can occur on a much faster time scale (KHz range) than the
7 conventional valve and pump technology used in ALD (up to minutes per
8 cycle), this deposition method is more suitable for commercial IC
9 manufacturing. This method shall be referred to herein as modulated ion-
10 induced atomic layer deposition (MII-ALD).

11 In addition, the present invention also improves upon the prior art by
12 employing a microwave generated plasma 172 substantially contained in the
13 main chamber body 190 that is isolated via a distribution showerhead 171
14 comprised of a series or array of apertures 175 which resolves the issues of
15 radical generation and delivery, while preventing gas-phase precursor
16 cracking (i.e., fragmentation or breaking down the precursor gas into its
17 constituent elements) and impurity and/or particle generation directly above
18 the wafer 181. The plasma is contained within the plasma source chamber 170
19 itself and is not in direct communication with the substrate 181. In MII-ALD,
20 the same plasma is used to generate both ions 177 (used to drive the surface
21 reactions) and radicals 176 (used as the second reactant), but is isolated from
22 the first reactant 100 which typically contains both the principal element(s)
23 desired in the end film, but also unwanted impurity containing byproducts.
24 Therefore, primarily only the radicals 176 and ions 177 are able to travel

1 through the showerhead apertures 175. The plasma 172 is essentially
2 contained within the plasma source chamber and does not intermingle with
3 the precursor gases 100, 120.

4 The present invention utilizes ion imparted kinetic energy transfer
5 rather than thermal energy (e.g., REALD, ALD, PECVD, CVD, etc.) to drive
6 the deposition reaction. Since temperature can be used as a secondary control
7 variable, with this enhancement films can be deposited using MII-ALD at
8 arbitrarily low substrate temperatures (generally less than 350 °C). In
9 particular, films can be deposited at or near room temperature (i.e., 25°C) or
10 below.

11 The system of Figure 1 contains a substantially enclosed plasma source
12 chamber 170 located in substantial communication with or, more preferably,
13 substantially within a main chamber body 190. The plasma 172 is used to
14 dissociate feed gases 130, 110 to generate both ions 177 and radicals 176.
15 Typical feed gases 130 used for ion generation include, but are not restricted
16 to Ar, Kr, Ne, and Xe. Typical feed gases 110 (e.g., precursor B) used for
17 radical generation include, but are not restricted to H₂, O₂, N₂, NH₃, and H₂O
18 vapor. The ions 177 are used to deliver the energy needed to drive surface
19 reactions between the first adsorbed reactant and the generated radicals 176.
20 Inductively coupled RF (e.g., 400 KHz, 2 MHz, 13.56 MHz, etc.) power 160 can
21 be used to generate the plasma via solenoidal coils located within or outside
22 of the plasma chamber (not shown in Figure 1). More preferably, microwave
23 (e.g., generally 2.45 GHz or higher frequencies) power 160 is coupled to the
24 plasma source chamber 170 via a suitable means such as a waveguide or

1 coaxial cable. Microwave energy can be more efficiently transferred to
2 ionizing electrons, leading to higher ionization fractions. This is of particular
3 importance in the generation of radicals 176 (i.e., a chemical fragment of a
4 larger molecule) such as atomic hydrogen, or any of a number of other
5 reactive groups such as nitrogen atoms (N), oxygen atoms (O), OH molecules,
6 or NH molecules, or a combination thereof. These radicals serve as the
7 second reactant. Microwave or radio-frequency (RF) power 160 is coupled to
8 the plasma 172 via a dielectric material 173, which may be a dielectric window
9 such as quartz embedded in the chamber wall, or it may be empty space in
10 the case of a microwave or RF antenna located within the plasma chamber.

11 In addition, a distribution showerhead 171, containing a series or array
12 of apertures 175 through which ions 177 and radicals 176 are delivered to the
13 substrate 181, isolates the main process chamber 180 from the plasma source
14 chamber 170. A pressure drop (for example, a 5 or 10 times decrease in
15 pressure, with the main processing chamber 180 being at the lower pressure)
16 is thereby created between the plasma source chamber 170 and the main
17 processing chamber 180 to project the ions 177 and radicals 176 to the
18 substrate 181 via the distribution showerhead 171. The plasma source
19 chamber 170 is generally of comparable diameter to the main chamber body
20 190 to enable large area exposure of the sample. The size, aspect ratio, and
21 distribution of the showerhead apertures 175 can be optimized to provide
22 uniform exposure of the substrate 181 and the desired ion 177 to radical 176
23 ratio. The distance between this showerhead 171 and the substrate 181 may
24 vary depending on the application. For the processing of wafers in the IC

1 industry, this distance is preferably at most two wafer diameters and more
2 preferably less than or equal to one half a wafer diameter.

3 Having a substantially enclosed plasma generation chamber 170
4 situated within the main chamber 190 allows efficient and uniform delivery of
5 ions 177 and radicals 176 to the substrate 181. In addition, by isolating the
6 plasma 172 from the main chamber 180 prevents gas-phase cracking of the
7 first reactant 100 (e.g., precursor A), which is introduced directly to the main
8 processing chamber 180 via a gas distribution manifold 199. Precursor A 100
9 may be any one or more of a series of gaseous compounds used for depositing
10 semiconductors, insulators, metals or the like that are well-known in the art
11 (e.g., PDEAT (pentakis(diethylamido)tantalum), PEMAT
12 (pentakis(ethylmethyldamido)tantalum), TaBr₅, TaCl₅, TBTDET (t-butyldimino
13 tris(diethylamino) tantalum), TiCl₄, TDMAT
14 (tetrakis(dimethylamido)titanium), TDEAT (tetrakis(diethylamino)titanium),
15 CuCl, Cupraselect® ((Trimethylvinylsilyl)hexafluoroacetylacetonato Copper
16 I), W(CO)₆, WF₆, etc.) and examples will be further discussed herein. Finally,
17 the ion/radical distribution showerhead 171 shields the dielectric wall 173
18 adjacent to the supplied RF or microwave power 160 against being coated by
19 precursor A 100 during processing which can degrade power transfer to the
20 plasma 172 in processing systems found in the prior art. This is of particular
21 importance in the case of deposition of conductors whereby if the dielectric
22 173 is fully exposed to the metal containing first reactant 100 (e.g., precursor
23 A) and if the plasma 172 was directly generated within the main chamber 190
24 without the use of an isolating distribution showerhead 171, then metal

1 deposition onto the dielectric 173 will eventually shield out RF or microwave
2 power 160 from the plasma 172 such that the plasma 172 will extinguish.

3 Figure 2A depicts a sequence for an improved ALD method
4 incorporating periodic exposure of the substrate to ions. In this variant of the
5 method, ion exposure 230 begins with the introduction of the second
6 precursor 220 (especially when plasma generated radicals 176 are used as the
7 second precursor or reactant). This figure illustrates one embodiment of MII-
8 ALD utilizing the apparatus described in Figure 1. This results in an
9 enhanced sequential ALD process as follows:

- 10 1) First exposure 200: The substrate 181 is exposed to a first gaseous
11 reactant 100 (e.g., precursor A), allowing a monolayer of the reactant to form
12 on the surface. The substrate 181 may be at any temperature below the
13 decomposition temperature of the first gaseous reactant although it is
14 preferable for the temperature to generally be less than approximately 350 °C.
- 15 2) First evacuation 210: The excess reactant 100 is removed by
16 evacuating 214 the chamber 180 with a vacuum pump 184.
- 17 3) Second exposure 220: Unlike conventional ALD, the substrate 181 is
18 simultaneously exposed to ions 177 and a second gaseous reactant (e.g.,
19 microwave or RF plasma generated radicals 176) during this step with the
20 substrate 181 (e.g., wafer) biased to a negative potential V_{bias} 185. Microwave
21 or RF power 160 is supplied into the plasma chamber 170 to generate both the
22 ions 177 (e.g., argon-ion (Ar^+)) and radicals 176 (e.g., H atoms). The ions will
23 strike the wafer 181 with an energy approximately equal to $(e|V_{bias}| + e|V_p|)$
24 where V_p is the plasma 172 potential (typically 10V to 20V). V_{bias} (-20V to -

1 500V) is typically chosen to be greater than V_p in magnitude, and is used to
2 control the ion 177 energy. With the activation energy now primarily
3 supplied by ions 177 instead of thermal energy, the first and second (chemi-
4 or physisorbed) reactants react via an ion-induced surface reaction to
5 produce a solid thin monolayer of the desired film at a reduced substrate
6 temperature below conventional ALD. The deposition reaction between the
7 first and second reactants is self-limiting in that the reaction between them
8 terminates after the initial monolayer of the first reactant 100 is consumed.

9 4) Second evacuation 210: The excess second reactant is removed by
10 again evacuating 216 the chamber 180 with the vacuum pump 184.

11 5) Repeat: The desired film thickness is built up by repeating the entire
12 process cycle (steps 1-4) many times.

13 Additional precursor gases (e.g., 120, 140) may be introduced and
14 evacuated as required for a given process to create tailored films of varying
15 compositions or materials. As an example, an optional exposure may occur in
16 the case of a compound barrier of varying composition. For example, a
17 TaN_x /Ta film stack is of interest in copper technology since TaN_x prevents
18 fluorine attack from the underlying fluorinated low-k dielectrics, whereas the
19 Ta promotes better adhesion and crystallographic orientation for the
20 overlying copper seed layer. The TaN_x film may be deposited using a
21 tantalum containing precursor (e.g., $TaCl_5$, PEMAT, PDEAT, TBTDET) as the
22 first reactant 100 (precursor A) and a mixture of atomic hydrogen and atomic
23 nitrogen (i.e. flowing a mixture of H_2 and N_2 into the plasma source 172) as
24 the second reactant to produce a TaN_x film. Simultaneous ion exposure is

1 used to drive the deposition reaction. Next a Ta film may be deposited in a
2 similar fashion by using atomic hydrogen (as opposed to a mixture of atomic
3 hydrogen and nitrogen) as the second reactant. An example of a tailored film
4 stack of differing materials can be the subsequent deposition of a copper layer
5 over the TaN_x /Ta bi-layer via the use of a copper containing organometallic
6 (e.g., $\text{Cu}(\text{TMVS})(\text{hfac})$ or (Trimethylvinylsilyl)hexafluoroacetylacetonato
7 Copper I, also known by the trade name CupraSelect®, available from
8 Schumacher, a unit of Air Products and Chemicals, Inc., 1969 Palomar Oaks
9 Way, Carlsbad, CA 92009) or inorganic precursor (e.g. CuCl) shown as
10 precursor C 120 in Figure 1. The copper layer can serve as the seed layer for
11 subsequent electroless or electroplating deposition.

12 A variant of the method shown in Figure 2A is illustrated in Figure 2B
13 where ion exposure is initiated after the second reactant exposure. Figure 2B
14 depicts a sequence for an improved ALD method incorporating periodic
15 exposure of the substrate 181 to ions 177. In this variant of the method, ion
16 exposure 280 begins with the evacuation 250 of the second precursor 256
17 (especially when the second precursor or reactant is not subjected to a
18 plasma). Typically, this is the case where the second precursor or reactant is
19 not a plasma-generated radical.

20 In the previous embodiments of MII-ALD, although the deposition
21 temperature can be lowered significantly, the first and second reactants are
22 still sequentially introduced into the main process chamber 180, and hence
23 will still be a slow process. It is of particular interest to eliminate or replace

1 the time-consuming flow-evacuation-flow-evacuation sequential nature of the
2 process.

3 In the preferred embodiment of the MII-ALD process, a substrate 181
4 heated (e.g., to a low temperature of less than or equal to 350 °C) or unheated
5 is simultaneously exposed to a first reactant and a second reactant, and
6 subjected to modulated ion 177 exposure. By modulating 1) the ion flux (i.e.
7 the number of ions hitting the substrate per unit area per unit time); 2) the
8 energy of the ions striking the substrate; or a combination of (1) and (2), the
9 deposition reaction can be precisely toggled "on" or "off". Since the substrate
10 181 is preferably maintained at a low substrate temperature, the first and
11 second reactants do not thermally react with any appreciable rate or do not
12 react at all when the ion flux or energy is toggled to a "low" state. Instead,
13 the deposition reaction only takes place when either the ion flux or ion energy
14 is toggled to a suitable "high state". Ion flux or energy modulation can vary
15 generally from 0.1 Hz to 20 MHz, preferably from 0.01 KHz to 10 KHz.
16 During deposition, the main process chamber 180 pressure can be maintained
17 in the range of generally 10^2 to 10^7 torr, more preferably from 10^1 to 10^4 torr,
18 depending on the chemistry involved. The desired film thickness is attained
19 via exposure of the substrate to the suitable number of modulated ion flux or
20 energy pulse cycles. This MII-ALD scheme results in a "continuous"
21 deposition process that is significantly faster than conventional sequential
22 ALD since the two, slow evacuation steps (up to minutes) are eliminated and
23 replaced by the faster (KHz range or above) ion modulation steps. The

1 modulation can be either of the ion flux via the plasma power or of the ion
2 energy via an applied periodic wafer bias.

3 The MII-ALD method utilizing ion flux modulation to control the
4 deposition cycle is illustrated conceptually in Figure 3A, with the flux
5 modulation scheme described more explicitly in Figures 4A and 4C. Figure
6 3A depicts the MII-ALD method utilizing ion flux modulation 320 to vary the
7 substrate 181 exposure to ions 177. Note that the second reactant 310, e.g.,
8 radicals, is synchronized with the ion flux via 320 plasma power modulation,
9 causing a periodic exposure of the substrate to ions and radicals. Varying the
10 power 160 delivered to the plasma 172 can vary the ion flux from little or
11 none to maximum ion production. Plasma power modulation can take the
12 form of variations in frequency (periodicity), magnitude, and duty-cycle.
13 Increasing plasma power 160 leads to increasing plasma 172, and hence,
14 increased ion 177 density. Since the deposition process is ion-induced, having
15 little or no ion bombardment will essentially stop the deposition process,
16 whereas increased ion bombardment will cause deposition to occur. A
17 constant wafer bias 185 (DC in Figure 4C or RF in Figure 4A) is applied to
18 define the ion energy of the modulated ion flux in this embodiment and is
19 chosen to be sufficiently high so that ion-induced surface reactions can occur.
20 Note that in this embodiment since the plasma (either RF or preferably
21 microwave) power 160 is used to generate both ions 177 and radicals 176, the
22 second reactant (e.g., radicals) flux 310 is synchronized with the ion flux 320
23 pulses. The radical feed gas 110 (H_2 for example) flow, however, does not

1 change. Instead, the radical flux 310 (e.g., fraction of H_2 which is converted to
2 atomic H) is modulated.

3 Alternatively, subjecting the substrate 181 to a non-constant wafer
4 voltage bias 185 can vary the incoming ion energy at a fixed plasma power
5 160 (i.e., ion flux). This preferred embodiment of MII-ALD is illustrated
6 conceptually in Figures 3B, and more explicitly in Figures 4B and 4D. Figure
7 3B shows the MII-ALD method utilizing ion energy modulation 350 to vary
8 the substrate 181 exposure to ions 177 by varying the substrate bias 185. The
9 applied bias 185 can take the form of variations in frequency (periodicity),
10 magnitude, and duty-cycle. A DC as shown in Figure 4D or RF (e.g., 400
11 kHz, 2 MHz, 13.56 MHz, etc.) as shown in Figure 4B power supply can be
12 used. When the wafer potential is "low" (e.g., near or at zero with respect to
13 ground), the incoming ions 177 do not have enough energy to induce surface
14 deposition reactions. When the wafer 181 potential is "high" (e.g., at a
15 significant negative potential relative to ground), the incoming ions 177 will
16 have the necessary energy to induce surface deposition reactions via collision
17 cascades. In such a fashion, the deposition can be turned "on" or "off" by
18 modulating the wafer bias voltage 185, and hence the impinging ion 177
19 energy. Typical wafer voltages can range from generally -20 V to -1000 V,
20 but preferably in the -25 V to -500 V range, and more preferably in the -50 V
21 to -350 V range during deposition. The bias voltage 185 is coupled to the
22 wafer via the pedestal 182. Preferably, the substrate pedestal 182 is an
23 electrostatic chuck (ESC) to provide efficient coupling of bias voltage to the
24 substrate. The ESC is situated in the main processing chamber 180 and can be

1 cooled via a fluid coolant (preferably a liquid coolant) and/or heated (e.g.,
2 resistively) to manipulate the substrate temperature.

3 As illustrated in Figure 5 for the case of an applied DC bias, the
4 preferred electrostatic chuck is a "coulombic" ESC 500 (bulk resistivity
5 generally greater than 10^{13} ohm-cm) rather than one whose bulk material
6 effects are dominated by the Johnson-Rahbek (JR) effect (bulk resistivity
7 between 10^8 and 10^{12} ohm-cm). Typically, the substrate potential is a complex
8 function of the voltage of the electrostatic "chucking" electrodes if these
9 voltages are established relative to a reference potential, but is simplified in
10 the case of "coulombic" (non-JR) ESC. However, if the power supply 510 that
11 powers the ESC 500 is truly floating, i.e., the entire system has a high
12 impedance to the chamber 180 potential (usually ground) including the
13 means of supplying power, then the substrate potential can be arbitrary. In
14 particular, if the ESC power supply 510 is also center-tapped 518, then the
15 wafer potential can be established by connecting the center tap 518 to the
16 output of a power amplifier 520. This power amplifier can be controlled by a
17 computer or a waveform generator 530 to periodically drop the substrate
18 potential to a negative value for a certain period of time. It is desired to have
19 independent control of the magnitude, frequency (periodicity), and duty cycle
20 of this substrate bias pulse train. Such an ESC system is depicted in Figure 5,
21 which shows an ESC system suitable for modulating the ion energy in the
22 MII-ALD process: a) in topological form; and, b) as an equivalent electrical
23 circuit.

1 The deposition rate is affected by the choice of the critical bias pulse
2 train variables: the magnitude, frequency (periodicity), and duty cycle.
3 Preferably, when the bias frequency is high (e.g., 100 Hz-10 KHz) with a short
4 duty cycle (e.g., less than 30%), reducing the net, time-averaged current
5 (which can cause substrate potential drift, de-chucking problems, or charge-
6 induced device damage) while providing a charge relaxation period wherein
7 the ion charges accumulated during ion exposure can redistribute and
8 neutralize.

9 Once the deposition rate is calibrated for a particular recipe
10 (Angstroms/cycle), the ability to accurately determine the film thickness by
11 counting cycles is a further benefit of this modulation scheme. The higher the
12 frequency, the finer the resolution of this critical deposition process
13 performance metric.

14 Alternatively, the substrate potential can be modulated by imparting
15 an induced DC bias to the substrate by applying RF power to the pedestal.
16 Preferably, the RF power is coupled into the ESC electrodes. Figures 4A-F
17 illustrate the preferred methods of modulating the MII-ALD process. In
18 Figure 4A, an RF bias power B_2 is applied to the substrate pedestal 182
19 imparting an induced DC bias V_2 to the substrate while the plasma (either
20 microwave or RF) power 400 is varied periodically between a high P_1 and a
21 low P_2 power state. In Figure 4B, plasma (either microwave or RF) power 410
22 is constant P_1 while an RF bias power, applied to the substrate pedestal 182, is
23 varied between a low B_1 and a high B_2 bias state (V_1 and V_2 are the DC offset or
24 bias voltages resulting from the applied RF bias power). In Figure 4C, a

1 negative DC bias 425 is applied to the substrate pedestal 182 while the plasma
2 (either microwave or RF) power 420 is varied periodically between a high P_1
3 and a low power P_2 state. In Figure 4D, plasma (either microwave or RF)
4 power is constant 430 while a DC bias 435 applied to the substrate pedestal
5 182 is varied between a zero V_1 and a negative voltage state V_2 . In Figure 4E,
6 a mechanical shutter periodically occludes the ion source. All the while, the
7 plasma power 440 (either microwave or RF) and substrate voltage 445 are
8 held constant. In Figure 4F, a source area that is smaller than the substrate
9 181 is preferably used. In this case, plasma (either microwave or RF) power
10 450 is constant, a negative DC substrate bias 455 is constant, and the source
11 and substrate 181 are moved relative to each other 457, exposing only a
12 portion of the substrate 181 at a time. The methods proposed in Figure 4B
13 and Figure 4D, whereby the substrate bias is modulated at a constant plasma
14 power 410, 430 and hence ion flux, are most preferred.

15 MII-ALD can be used to deposit dielectric, semiconducting, or metal
16 films, among others, used in the semiconductor, data storage, flat panel
17 display, and allied as well as other industries. In particular, the method and
18 apparatus is suitable for the deposition of barrier layers, adhesion layers, seed
19 layers, low dielectric constant (low-k) films, and high dielectric constant
20 (high-k) films.

21 This process utilizes independent control over the three constituents of
22 plasma – ions, atoms, and precursors. Decoupling these constituents offer
23 improved control over the deposition process.

1 An added benefit of using MII-ALD is that with proper choice of the
2 second reactant, selective ion-enhanced etching and removal of unwanted
3 impurities can be performed. As an example, for many chemistries, the
4 preferred second reactant is monatomic hydrogen (H) 176. Simultaneous
5 energetic ion and reactive atomic H bombardment will cause selective
6 removal of unwanted impurities (e.g., containing carbon, oxygen, fluorine, or
7 chlorine) commonly associated with organometallic precursors (e.g., TBTDET,
8 PEMAT, PDEAT, TDMAT, TDEAT), and proceed with removal rates superior
9 to either chemical reaction (e.g., atomic H only) or physical sputtering (e.g.,
10 Ar ion only) alone. Impurities lead to high film resistivities, low film density,
11 poor adhesion, and other deleterious film effects. Alternatively, in addition to
12 atomic hydrogen, other reactive groups such as nitrogen atoms (N), oxygen
13 atoms (O), OH molecules, or NH molecules, or a combination thereof may be
14 employed.

15 From the description of the preferred embodiments of the process and
16 apparatus set forth above, it is apparent to one of ordinary skill in the art that
17 variations and additions to the embodiments can be made without departing
18 from the principles of the present invention. As an example, chlorine,
19 bromine, fluorine, oxygen, nitrogen, hydrogen, other reactants and/or
20 radicals containing the aforementioned elements or a combination thereof, in
21 conjunction with energetic ion bombardment, can be used to effect etching or
22 material removal as opposed to deposition. This is of particular importance
23 in the cleaning of native oxides of copper, aluminum, silicon, and other
24 common conductor and semiconductor materials used in IC manufacturing.

- 1 Either the deposition or etching can be accomplished globally (as illustrated
- 2 in the preceding embodiments) or may be chosen to be local to a controlled
- 3 area (i.e., site-specific using a small, ion beam point or broad-beam source
- 4 scanned or otherwise stepped across the substrate, exposing only a fraction of
- 5 the substrate area at any given time).

System and Method for Modulated Ion-induced Atomic Layer Deposition (MII-ALD)

Claims

What is claimed is:

1 1. A sequential method for depositing a thin film onto a substrate
2 in an evacuated chamber comprising:
3 introducing a first reactant gas into said chamber;
4 adsorption of at least one monolayer of said first reactant gas onto said
5 substrate;
6 evacuation of excess said first reactant gas from said chamber
7 introduction of at least one ion generating feed gas into said chamber;
8 generating a plasma from said ion generating feed gas to form ions;
9 exposing said substrate to said ions;
10 modulating said ions; and
11 reacting said adsorbed monolayer of said first reactant gas with said
12 ions to deposit said thin film.

1 2. The method of claim 1, wherein said ion modulation is
2 modulated in a way selected from the group consisting of modulating an ion
3 flux and modulating an ion energy.

1 3. The method of claim 1, further comprising maintaining said
2 substrate at a temperature of between about 25 °C to 350 °C.

1 4. A system for ion-induced atomic layer deposition of a film onto
2 a substrate, said system comprising:
3 a main chamber containing a plasma generation chamber for
4 generating a plasma;
5 said main chamber also containing a deposition chamber for
6 depositing said film on said substrate;
7 a distribution showerhead located between said plasma generation
8 chamber and said deposition chamber;
9 said plasma generation chamber coupled to receive at least one feed
10 gas to form said plasma for generation of ions;
11 said plasma generation chamber also coupled to receive at least one
12 feed gas to react with said plasma for generation of radicals; and
13 said deposition chamber coupled to receive at least one precursor gas
14 to react with said ions and said radicals to form said film on said substrate.

1 5. The system of claim 4, wherein said plasma generation chamber
2 is in communication with a radio frequency energy source through a
3 dielectric window.

1 6. The system of claim 5, wherein said distribution showerhead
2 shields said dielectric window from being coated by said deposition chamber
3 precursor gas.

1 7. The system of claim 4, wherein said plasma generation chamber
2 is in communication with a microwave frequency energy source.

1 8. The system of claim 4 further comprising a substrate holder
2 located in said deposition chamber, said substrate holder electrically biasing
3 said substrate via a power supply.

1 9. The system of claim 8, wherein said power supply supplies a
2 radio frequency power to induce said electrical bias on said substrate.

1 10. The system of claim 4, wherein said plasma generated in said
2 plasma generation chamber does not intermingle with said deposition
3 chamber precursor gas.

1 11. The system of claim 4, wherein said distribution showerhead is
2 comprised of one or more apertures.

1 12. The system of claim 4, wherein a deposition reaction is
2 controlled via ion-imparted kinetic energy.

1 13. The system of claim 4, further comprising a thermal heating
2 element to control said film deposition on said substrate.

1 14. A system for generating a plasma for depositing a film onto a
2 substrate, said system comprising:
3 a plasma generation source;
4 a plasma generation chamber coupled to said plasma generation
5 source;
6 a deposition chamber; and
7 a distribution showerhead separating said plasma generation chamber
8 from said deposition chamber.

1 15. The system of claim 14, wherein said plasma generation source
2 may be modulated by a change selected from a group consisting of a change
3 in frequency, a change in power magnitude, and a change in duty-cycle.

1 16. A sequential method for depositing a thin film onto a substrate
2 in an evacuated chamber comprising:
3 introducing a first reactant gas into said chamber;
4 adsorption of at least one monolayer of said first reactant gas onto said
5 substrate;
6 evacuation of excess said first reactant gas from said chamber
7 introduction of at least one ion generating feed gas into said chamber;
8 introduction of at least one radical generating feed gas into said
9 chamber;
10 generating a plasma from said ion generating feed gas and said radical
11 generating feed gas to form ions and radicals;
12 exposing said substrate to said ions and said radicals;
13 modulating said ions; and
14 reacting said adsorbed monolayer of said first reactant gas with said
15 ions and said radicals to deposit said thin film.

1 17. The method of claim 16, wherein said method is repeated until
2 the film achieves a desired thickness.

1 18. The method of claim 16, further comprising exposing said
2 substrate to at least one additional reactant gas.

1 19. The method of claim 16, wherein said substrate is
2 simultaneously exposed to said ions and said radicals

1 20. The method of claim 16, wherein said ion modulation is
2 modulated in a way selected from the group consisting of modulating an ion
3 flux and modulating an ion energy.

1 21. The method of claim 20, wherein modulation in said ion flux is
2 modulated in a way selected from the group consisting of modulating a flow
3 of said ion generating feed gas, modulating a power of said plasma,
4 modulating said exposure to said ions, and modulating the relative
5 movement between said plasma and said substrate.

1 22. The method of claim 16, further comprising maintaining said
2 substrate at a temperature of between about 25 °C to 350 °C.

1 23. The method of claim 16, further comprising inducing an
2 electrical bias on said substrate via a substrate pedestal on which said
3 substrate rests.

1 24. The method of claim 23, wherein said pedestal is an electrostatic
2 chuck (ESC) to provide coupling of said electrical bias to said substrate.

1 25. The method of claim 23, wherein said electrical bias is induced
2 by a radio frequency power supply.

1 26. The method of claim 16, wherein an energy to generate said
2 plasma is produced by a radio frequency source.

1 27. The method of claim 16, wherein an energy to generate said
2 plasma is produced by a microwave source.

1 28. A method for depositing a thin film onto a substrate in an
2 evacuated chamber comprising:
3 placing said substrate onto a substrate holder in a deposition chamber
4 area;
5 introducing at least one ion generating feed gas into a plasma
6 generation chamber area in communication with said deposition chamber
7 area, but substantially isolated via a distribution showerhead comprised of
8 one or more apertures located between said plasma generation chamber area
9 and said deposition chamber area;
10 introducing at least one radical generating feed gas into said plasma
11 generation chamber area;
12 generating a plasma from said ion generating feed gas to form ions;
13 generating a plasma from said radical generating feed gas to form
14 radicals;
15 electrically biasing said substrate to a negative potential;
16 introducing at least one reactant gas into said deposition chamber area;
17 adsorbing at least one monolayer of said reactant gas on said substrate;
18 exposing said substrate to said ions and said radicals;
19 modulating said ions; and
20 reacting said adsorbed monolayer of said reactant gas with said ions
21 and said radicals to deposit said thin film.

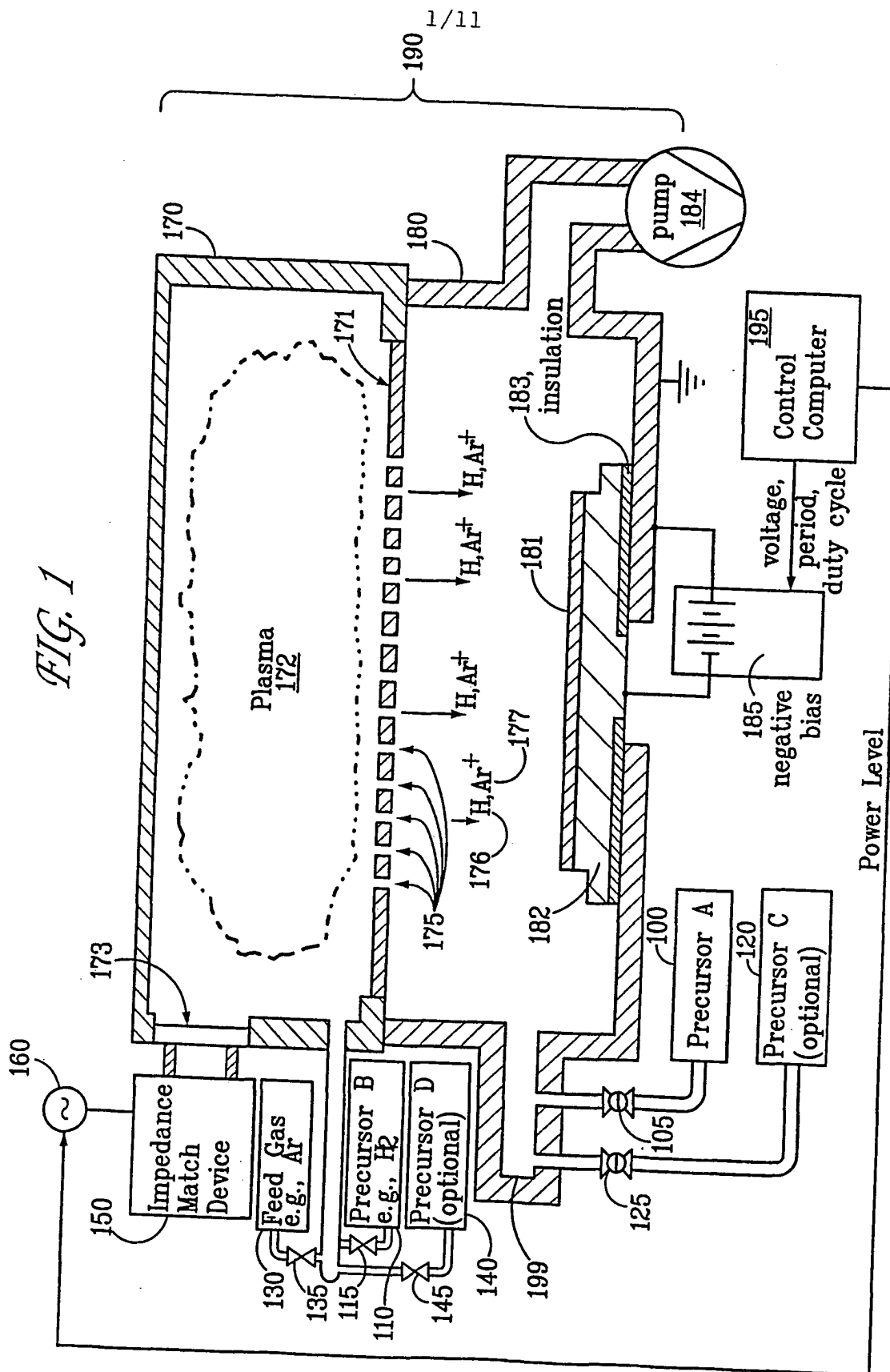
1 29. The method of claim 28, further comprising exposing said
2 substrate to at least one additional reactant gas.

1 30. The method of claim 28, further comprising exposing said
2 substrate to said reactant gas while varying exposure of said substrate to said
3 ions via said ion modulation.

1 31. The method of claim 30, wherein said ion modulation is effected
2 in a way selected from the group consisting of modulating an ion flux and
3 modulating an ion energy.

1 32. The method of claim 31, wherein modulation in said ion flux is
2 modulated in a way selected from the group consisting of modulating a flow
3 of said ion generating feed gas, modulating a power of said plasma,
4 mechanically occluding said ions, and modulating the relative movement
5 between said plasma and said substrate.

1 33. The method of claim 28, further comprising maintaining said
2 substrate at a temperature of between about 25 °C to 350 °C.



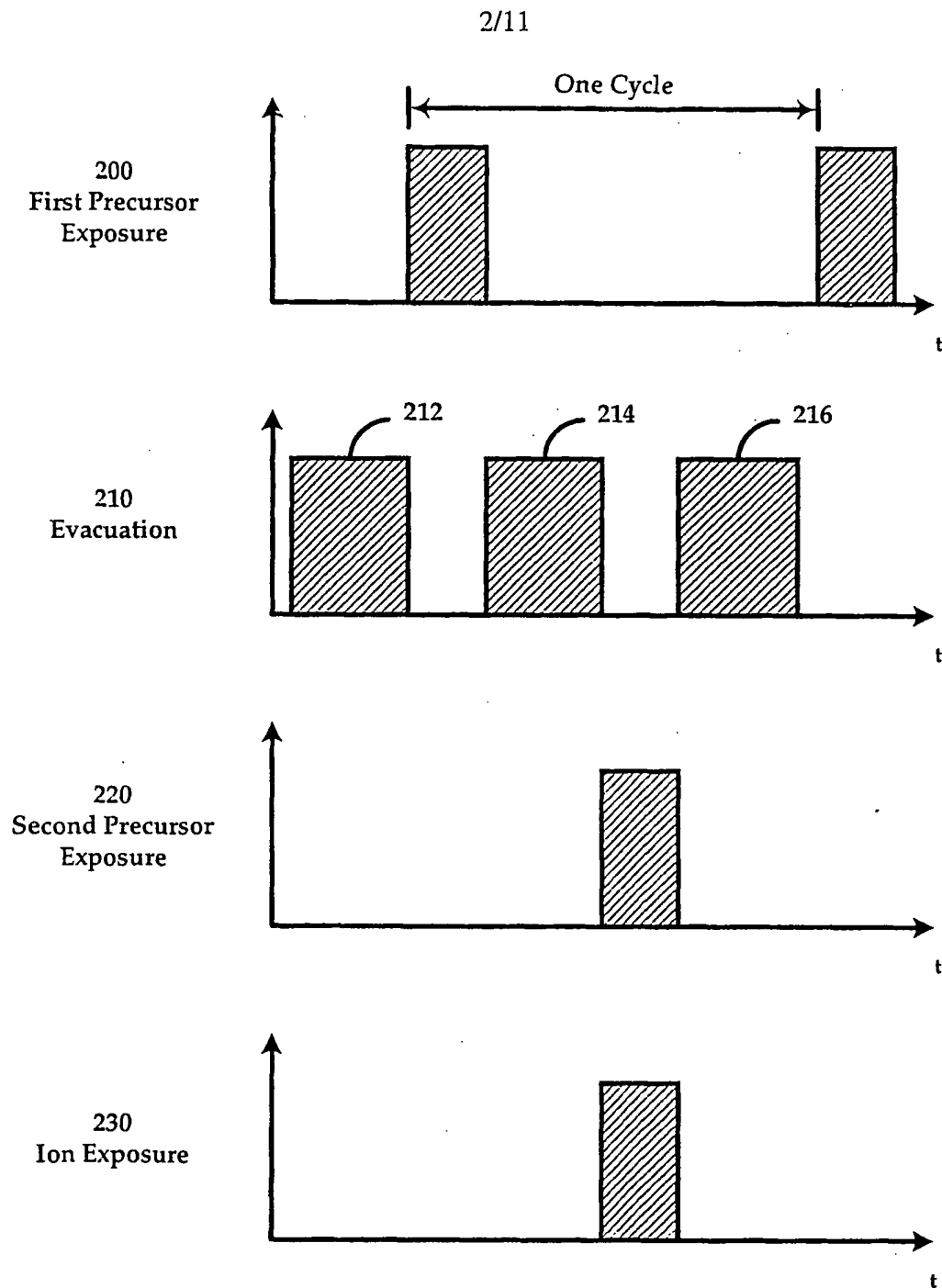


Figure 2A

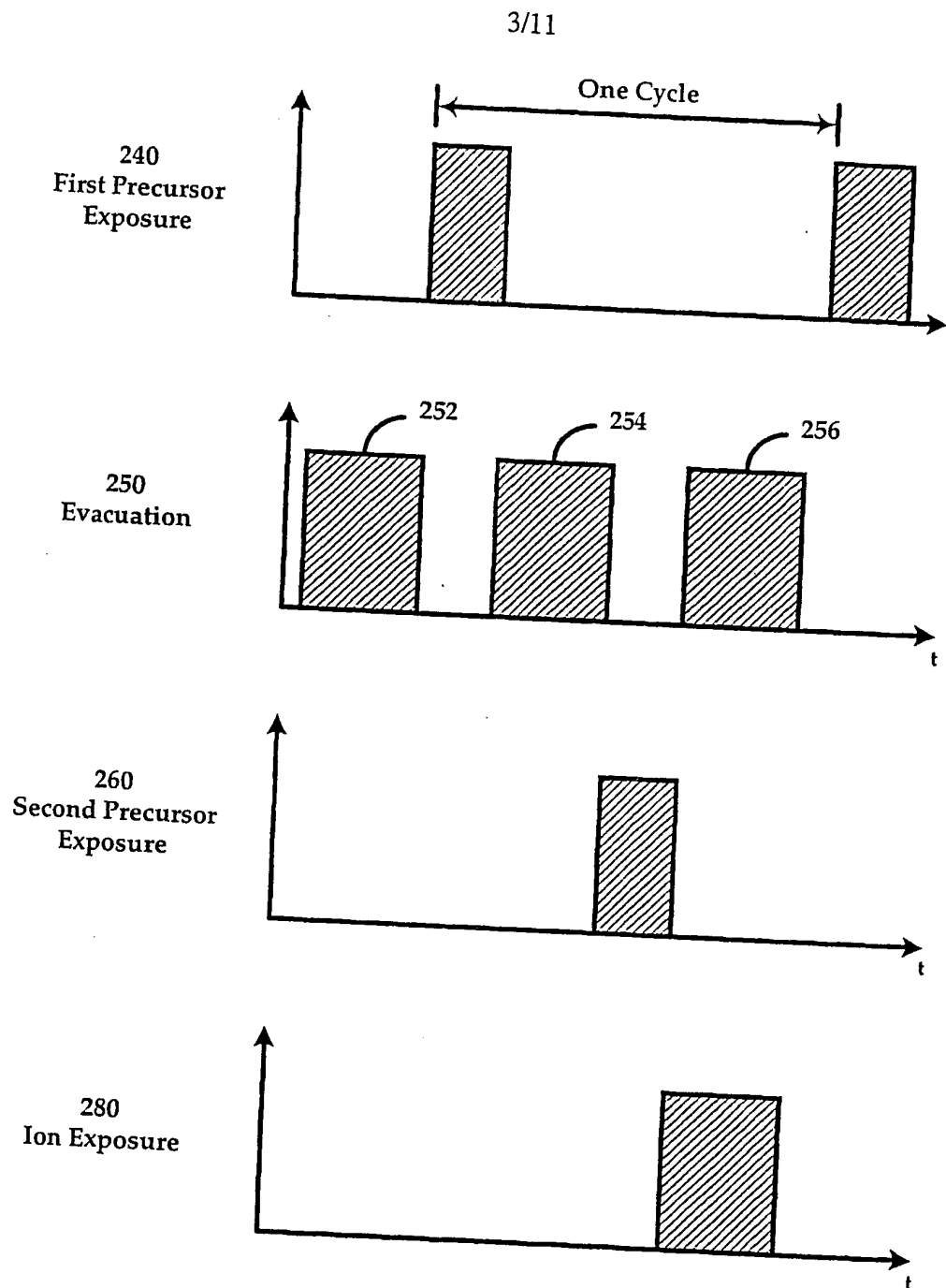


Figure 2B

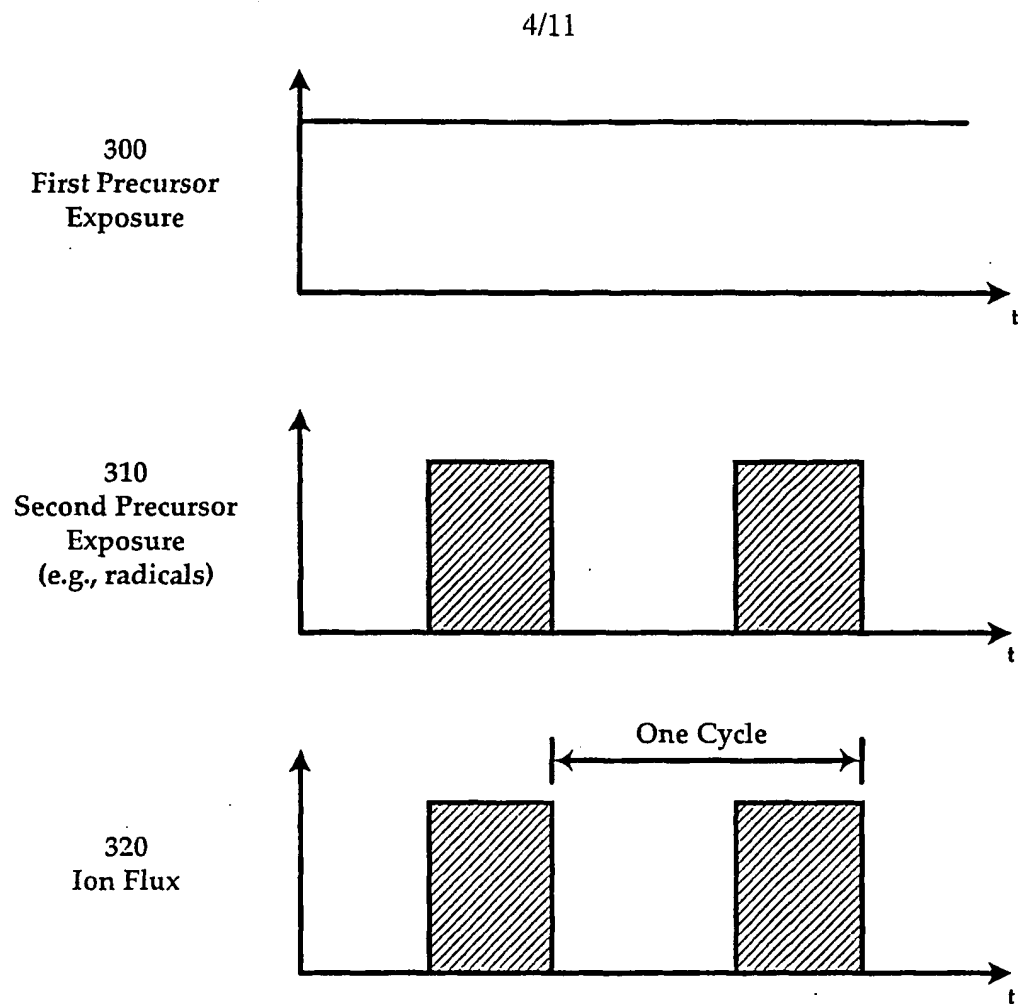
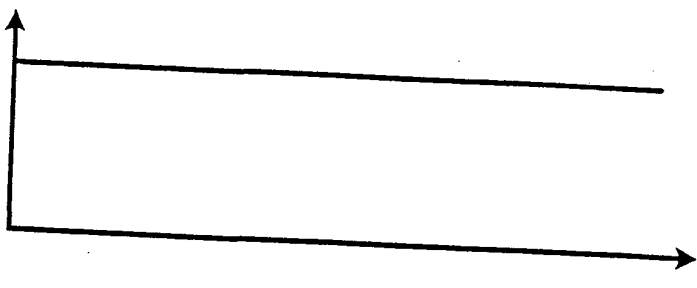


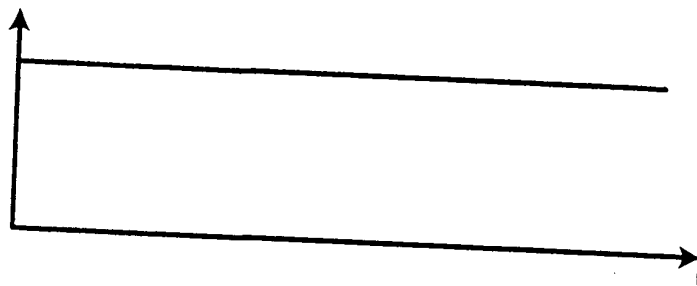
Figure 3A

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330
First Precursor
Exposure



340
Second Precursor
Exposure
(e.g., radicals)



350
Ion Energy

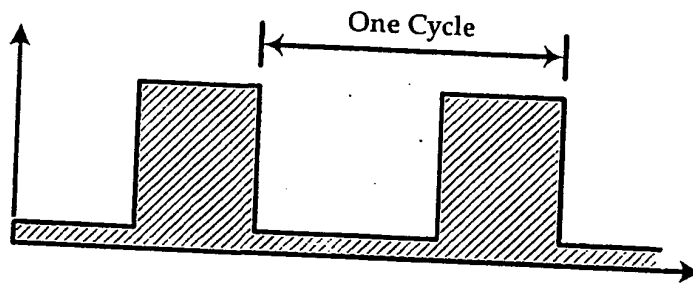


Figure 3B

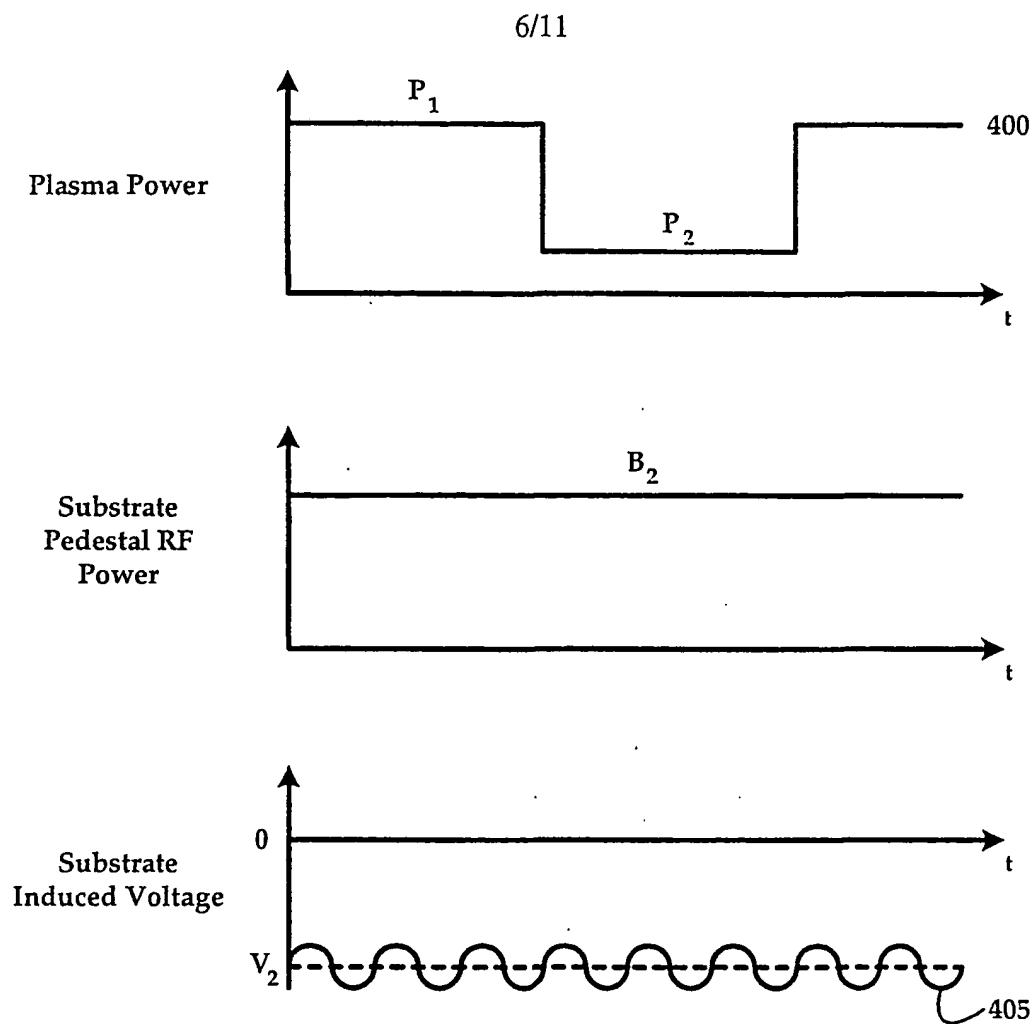


Figure 4A

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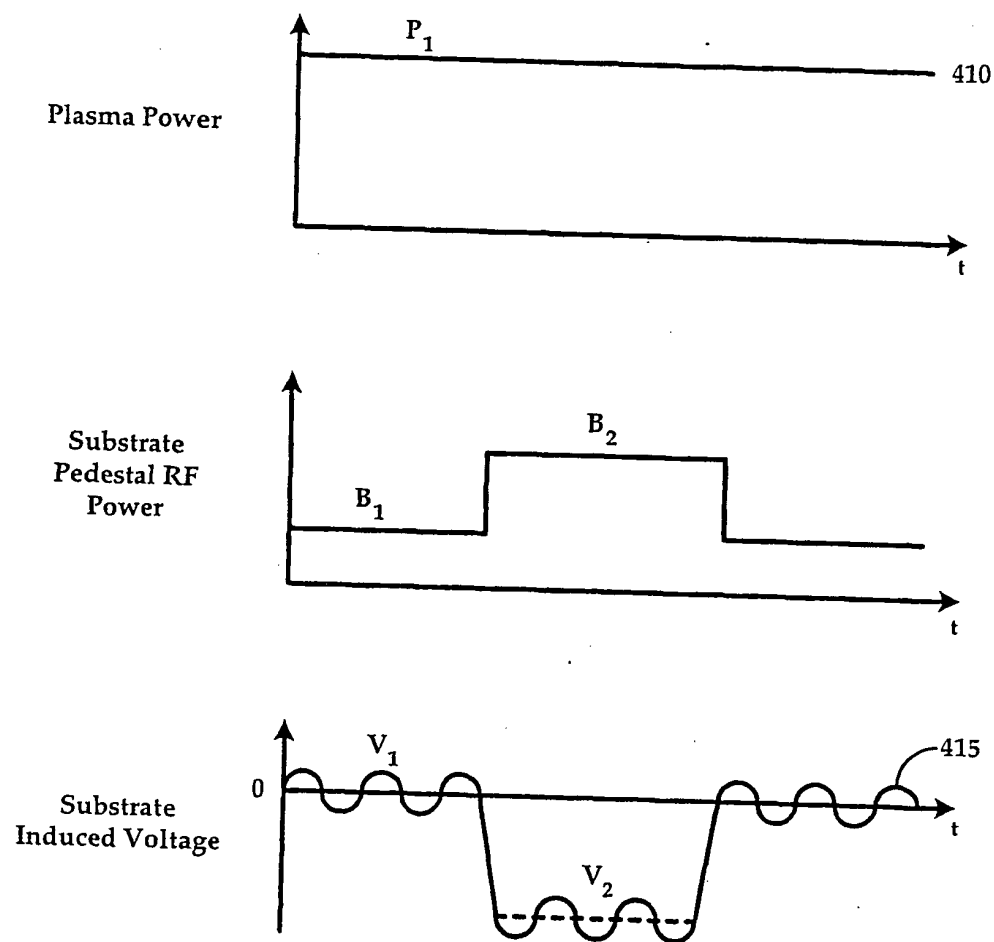


Figure 4B

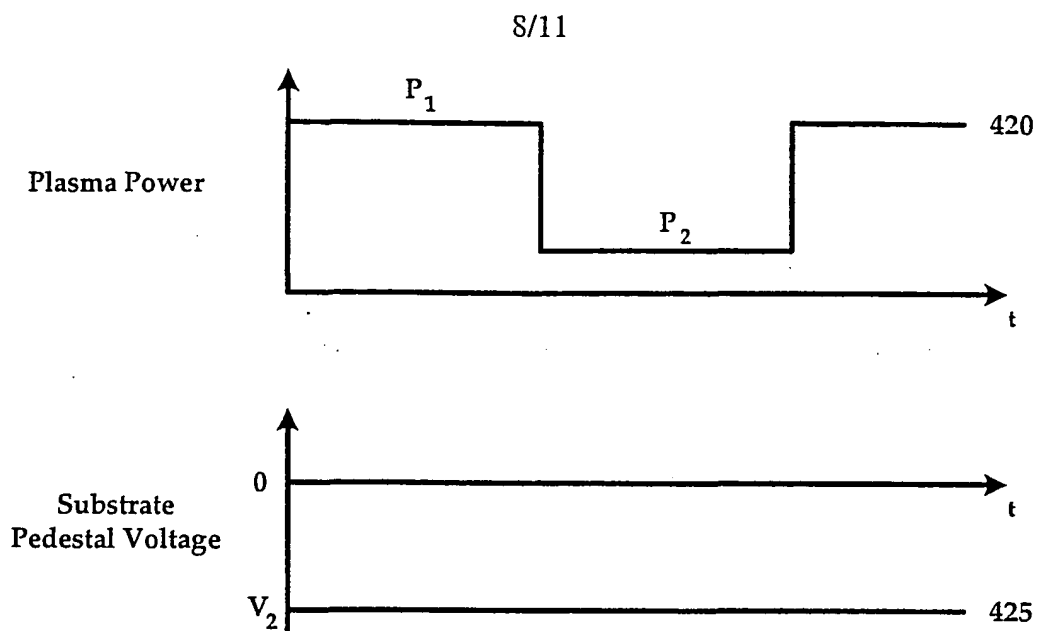


Figure 4C

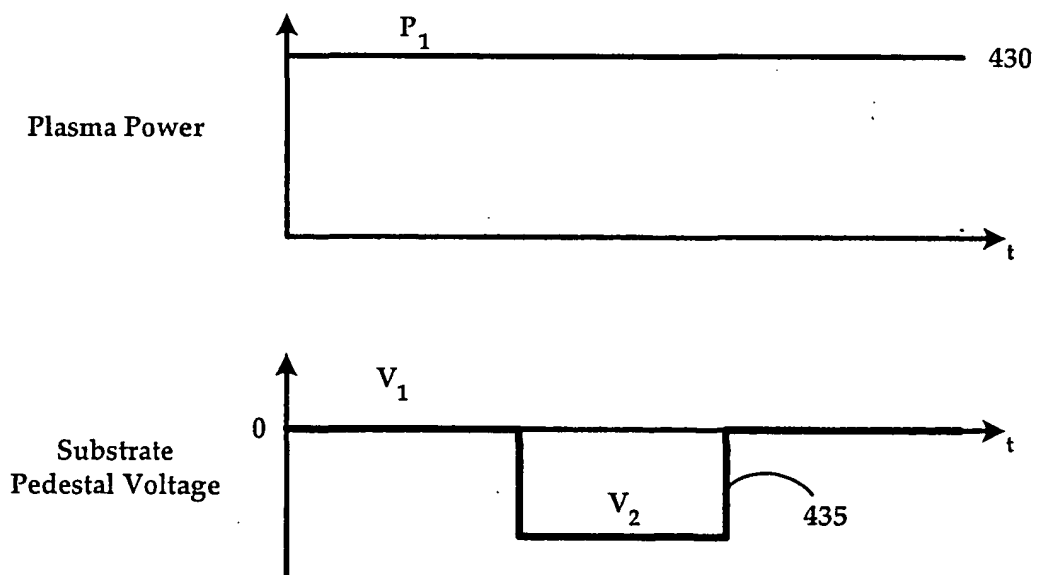


Figure 4D

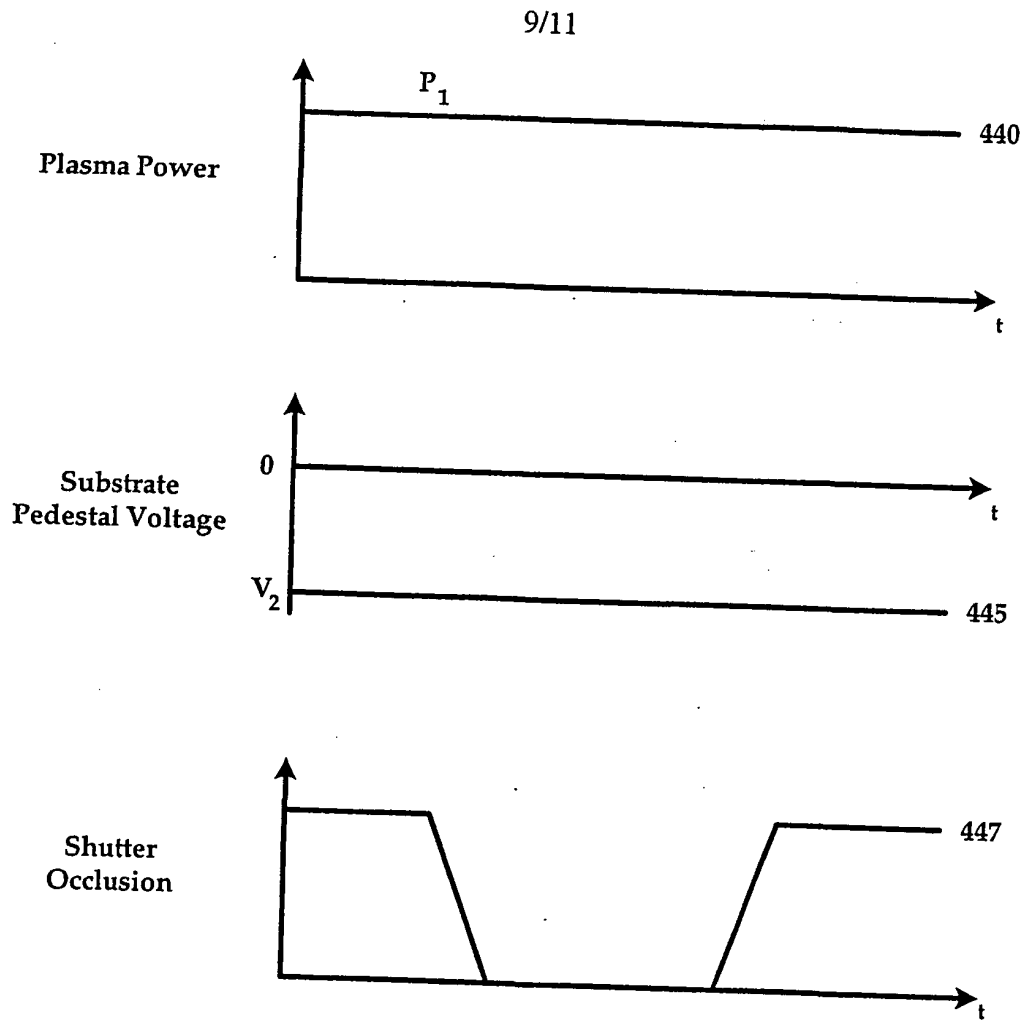


Figure 4E

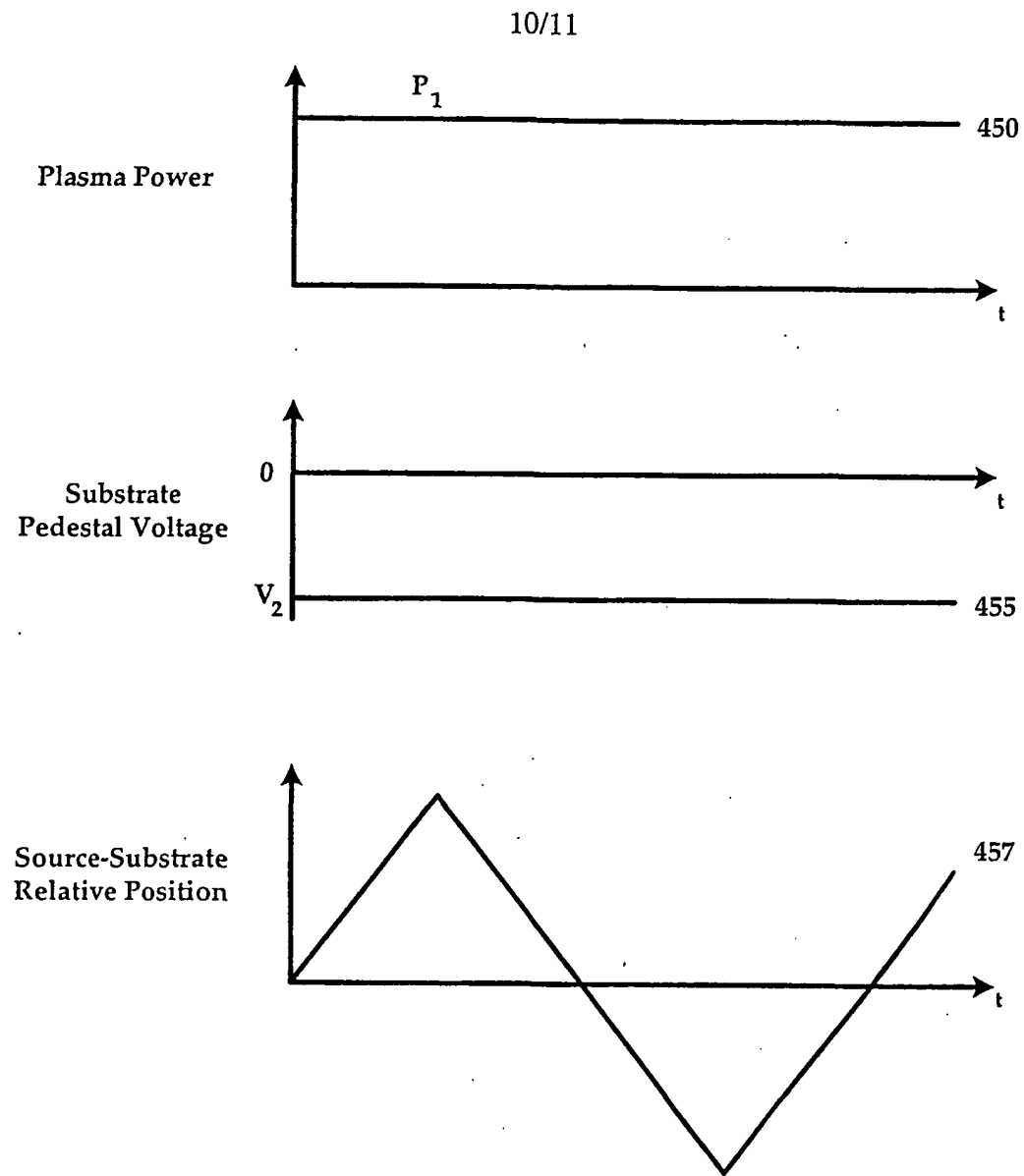


Figure 4F

11/11

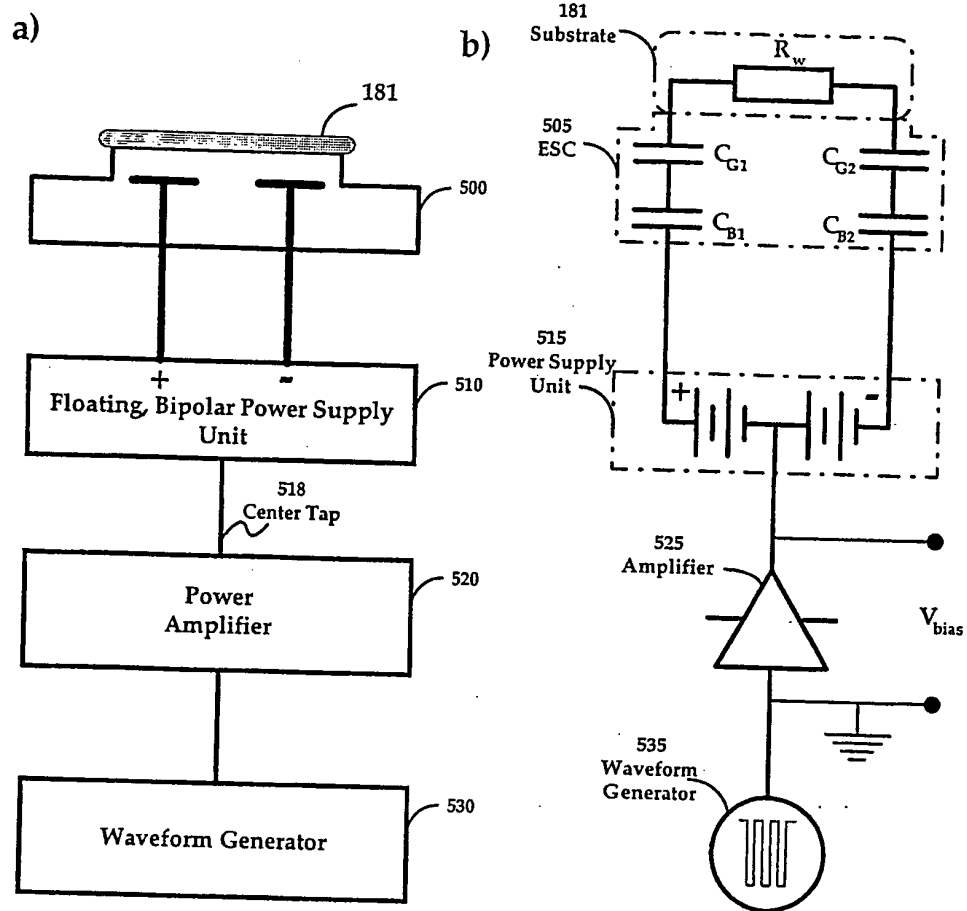


Figure
5

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US01/50350

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) : B05D 3/04; C23C 16/00, 16/44, 16/452, 16/455, 16/505, 16/511; C30B 25/00, 25/08, 25/14; H05H 1/24
 US CL : 427/561, 569, 570, 575, 248.1, 255.28, 255.5; 117/88, 92, 103, 105; 118/719, 723R, 723MW, 723I, 729

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
 U.S. : Please See Continuation Sheet

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
 none

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
 Please See Continuation Sheet

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- Y	US 5,916,365 A (SHERMAN) 29 June 1999 (29.06.1999), abstract, figures 1-3, columns 5-6, and column 7, lines 13-26.	1-3, 16-22, 26 ----- 23-25, 27
X,P --- Y,P	US 6,200,893 B1 (SNEH) 13 March 2001 (13.03.2001), abstract, figure 1, columns 3-6, column 7, lines 1-25, column 8, lines 5-15, column 10, lines 35-67, and column 11, lines 1-11.	1, 2, 16-21 ----- 3, 22-27
X --- Y	US 4,401,054 A (MATSUO et al) 30 August 1983 (30.08.1983), abstract, figures 3 and 6, columns 5-7, column 8, lines 1-5, column 9, lines 39-56, column 10, lines 20-65, columns 11-12, column 14, lines 60-67, and column 15, lines 1-3 and 36-38.	4, 7-15 ----- 5, 6, 23-25
Y	US 5,762,714 A (MOHN et al) 09 June 1998 (09.06.1998), column 2, lines 8-17.	24
Y	US 5,478,403 A (SHINAGAWA et al) 26 December 1995 (26.12.1995), column 7, lines 20-24.	5, 6, 27

☐ Further documents are listed in the continuation of Box C.

☐ See patent family annex.

* Special categories of cited documents:

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"T"

later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&"

document member of the same patent family

Date of the actual completion of the international search

11 March 2002 (11.03.2002)

Date of mailing of the international search report

04 APR 2002

Name and mailing address of the ISA/US

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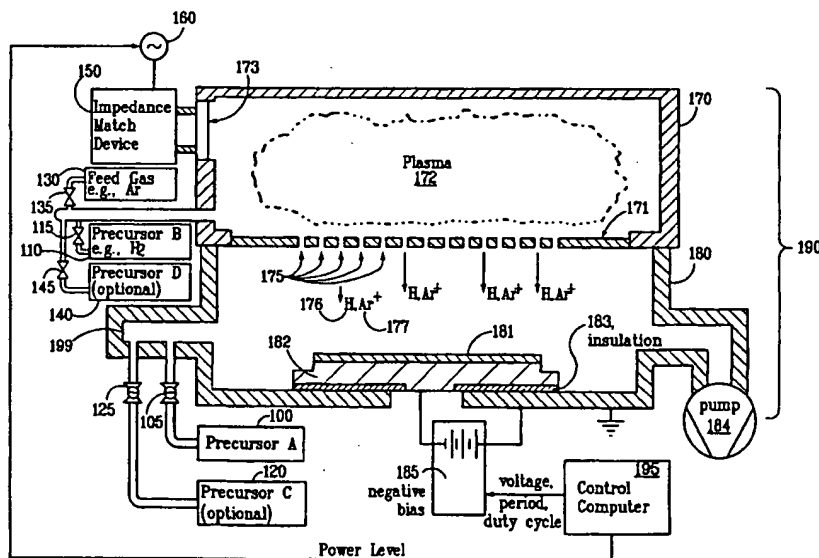
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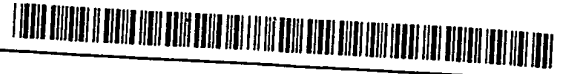
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(54) Title: SYSTEM AND METHOD FOR MODULATED ION-INDUCED ATOMIC LAYER DEPOSITION (MII-ALD)



(57) Abstract: The present invention relates to an enhanced sequential or non-sequential atomic layer deposition (ALD) apparatus and technique suitable for deposition of barrier layers, adhesion layers, seed layers, low dielectric constant (low-k) films, high dielectric constant (high-k) films, and other conductive, semi-conductive, and non-conductive films. This is accomplished by providing a non-thermal or non-pyrolytic means of triggering the deposition reaction; providing a means of depositing a purer film of higher density at lower temperatures; providing a means of modulating the deposition sequence and hence the overall process rate; and providing a means of improved radical (176) generation and delivery.

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**System and Method for Modulated Ion-induced Atomic Layer Deposition
(MII-ALD)**

Specification

Cross-Reference to Related Applications

1 This application claims the benefit of U.S. Provisional Application Nos.
2 60/251,795, and 60/254,280, both filed December 6, 2000, as well as U.S.
3 Utility Application Nos. 09/812, 285, 09/812,352, and 09/812,486, all filed
4 March 19, 2001, and U.S. Utility Application No. 09/854,092, filed May 10,
5 2001.

Background of the Invention

6
7
8 The present invention relates generally to the field of advanced thin
9 film deposition methods commonly used in the semiconductor, data storage,
10 flat panel display, as well as allied or other industries. More particularly, the
11 present invention relates to an enhanced sequential or non-sequential atomic
12 layer deposition (ALD) apparatus and technique suitable for deposition of
13 barrier layers, adhesion layers, seed layers, low dielectric constant (low-k)
14 films, high dielectric constant (high-k) films, and other conductive, semi-
15 conductive, and non-conductive thin films.

16 The disadvantages of conventional ALD are additionally discussed in a
17 copending application with the same assignee entitled "Method and
18 Apparatus for Improved Temperature Control in Atomic Layer Deposition",
19 which is hereby incorporated by reference in its entirety and may be found as
20 copending provisional, Application No. 09/854,092.

Brief Description of the Prior Art

1 As integrated circuit (IC) dimensions shrink and the aspect ratios of the
2 resulting features increase, the ability to deposit conformal, ultra-thin films on
3 the sides and bottoms of high aspect ratio trenches and vias becomes
4 increasingly important. These conformal, ultra-thin films are typically used
5 as "liner" material to enhance adhesion, prevent inter-diffusion and/or
6 chemical reaction between the underlying dielectric and the overlying metal,
7 and promote the deposition of a subsequent film.

8 In addition, decreasing device dimensions and increasing device
9 densities has necessitated the transition from traditional CVD tungsten plug
10 and aluminum interconnect technology to copper interconnect technology.
11 This transition is driven by both the increasing impact of the RC interconnect
12 delay on device speed and by the electromigration (i.e., the mass transport of
13 metal due to momentum transfer between conducting electrons and diffusing
14 metal atoms, thereby affecting reliability) limitations of aluminum based
15 conductors for sub 0.25 μm device generations. Copper is preferred due to its
16 lower resistivity and higher (greater than 10 times) electromigration resistance
17 as compared to aluminum. A single or dual damascene copper metallization
18 scheme is used since it eliminates the need for copper etching and reduces the
19 number of integration steps required. However, the burden now shifts to the
20 metal deposition step(s) as the copper must fill predefined high aspect ratio
21 trenches and/or vias in the dielectric. Electroplating has emerged as the
22 copper fill technique of choice due to its low deposition temperature, high
23 deposition rate, and potential low manufacturing cost.

24 Two major challenges exist for copper wiring technology: the barrier
25 and seed layers. Copper can diffuse readily into silicon and most dielectrics.
26 This diffusion may lead to electrical leakage between metal wires and poor
27 device performance. An encapsulating barrier layer is needed to isolate the
28 copper from the surrounding material (e.g., dielectric or Si), thus preventing
29 copper diffusion into and/or reaction with the underlying material (e.g.
30 dielectric or Si). In addition, the barrier layer also serves as the adhesion or

1 glue layer between the patterned dielectric trench or via and the copper used
2 to fill it. The dielectric material can be a low dielectric constant, i.e. low-k
3 material (used to reduce inter- and intra-line capacitance and cross-talk)
4 which typically suffers from poorer adhesion characteristics and lower
5 thermal stability than traditional oxide insulators. Consequently, this places
6 more stringent requirements on the barrier material and deposition method.
7 An inferior adhesion layer will, for example, lead to delamination at either the
8 barrier-to-dielectric or barrier-to-copper interfaces during any subsequent
9 anneal and/or chemical mechanical planarization (CMP) processing steps
10 leading to degradation in device performance and reliability. Ideally, the
11 barrier layer should be thin, conformal, defect free, and of low resistivity so as
12 to not compromise the conductance of the copper metal interconnect
13 structure.

14 In addition, electroplating fill requires a copper seed layer, which
15 serves to both carry the plating current and act as the nucleation layer. The
16 preferred seed layer should be smooth, continuous, of high purity, and have
17 good step coverage with low overhang. A discontinuity in the seed layer will
18 lead to sidewall voiding, while gross overhang will lead to pinch-off and the
19 formation of top voids.

20 Both the barrier and seed layers which are critical to successful
21 implementation of copper interconnects require a means of depositing high
22 purity, conformal, ultra-thin films at low substrate temperatures.

23 Physical vapor deposition (PVD) or sputtering has been adopted as the
24 preferred method of choice for depositing conductor films used in IC
25 manufacturing. This choice has been primarily driven by the low cost, simple
26 sputtering approach whereby relatively pure elemental or compound
27 materials can be deposited at relatively low substrate temperatures. For
28 example, refractory based metals and metal compounds such as tantalum
29 (Ta), tantalum nitride (TaN_x), other tantalum containing compounds,
30 tungsten (W), tungsten nitride (WN_x), and other tungsten containing
31 compounds which are used as barrier/adhesion layers can be sputter

1 deposited with the substrate at or near room temperature. However, as
2 device geometries have decreased, the step coverage limitations of PVD have
3 increasingly become an issue since it is inherently a line-of-sight process. This
4 limits the total number of atoms or molecules which can be delivered into the
5 patterned trench or via. As a result, PVD is unable to deposit thin continuous
6 films of adequate thickness to coat the sides and bottoms of high aspect ratio
7 trenches and vias. Moreover, medium/high-density plasma and ionized PVD
8 sources developed to address the more aggressive device structures are still
9 not adequate and are now of such complexity that cost and reliability have
10 become serious concerns.

11 Chemical vapor deposition (CVD) processes offer improved step
12 coverage since CVD processes can be tailored to provide conformal films.
13 Conformality ensures the deposited films match the shape of the underlying
14 substrate, and the film thickness inside the feature is uniform and equivalent
15 to the thickness outside the feature. Unfortunately, CVD requires
16 comparatively high deposition temperatures, suffers from high impurity
17 concentrations, which impact film integrity, and have higher cost-of-
18 ownership due to long nucleation times and poor precursor gas utilization
19 efficiency. Following the tantalum containing barrier example, CVD Ta and
20 TaN films require substrate temperatures ranging from 500 °C to over 800 °C
21 and suffer from impurity concentrations (typically of carbon and oxygen)
22 ranging from several to tens of atomic % concentration. This generally leads
23 to high film resistivities (up to several orders of magnitude higher than PVD),
24 and other degradation in film performance. These deposition temperatures
25 and impurity concentrations make CVD Ta and TaN unusable for IC
26 manufacturing, in particular for copper metallization and low-k integration.

27 Chen et al. ("Low temperature plasma-assisted chemical vapor
28 deposition of tantalum nitride from tantalum pentabromide for copper
29 metallization", J. Vac. Sci. Technol. B 17(1), pp. 182-185 (1999); and "Low
30 temperature plasma-promoted chemical vapor deposition of tantalum from
31 tantalum pentabromide for copper metallization", J. Vac. Sci. Technol. B 16(5),

pp. 2887-2890 (1998)) have demonstrated a plasma-assisted (PACVD) or plasma-enhanced (PECVD) CVD approach using tantalum pentabromide (TaBr_5) as the precursor gas to reduce the deposition temperature. Ta and TaN_x films were deposited from 350 °C to 450 °C and contained 2.5 to 3 atomic % concentration of bromine. Although the deposition temperature has been reduced by increased fragmentation (and hence increased reactivity) of the precursor gases in the gas-phase via a plasma, the same fragmentation leads to the deposition of unwanted impurities. Gas-phase fragmentation of the precursor into both desired and undesired species inherently limits the efficacy of this approach.

Recently, atomic layer chemical vapor deposition (AL-CVD) or atomic layer deposition (ALD) has been proposed as an alternative method to CVD for depositing conformal, ultra-thin films at comparatively lower temperatures. ALD is similar to CVD except that the substrate is sequentially exposed to one reactant at a time. Conceptually, it is a simple process: a first reactant is introduced onto a heated substrate whereby it forms a monolayer on the surface of the substrate. Excess reactant is pumped out. Next a second reactant is introduced and reacts with the first reactant to form a monolayer of the desired film via a self-limiting surface reaction. The process is self-limiting since the deposition reaction halts once the initially adsorbed (physi- or chemi-sorbed) monolayer of the first reactant has fully reacted with the second reactant. Finally, the excess second reactant is evacuated. The above sequence of events comprises one deposition cycle. The desired film thickness is obtained by repeating the deposition cycle the required number of times.

In practice, ALD is complicated by the painstaking selection of a process temperature setpoint wherein both: 1) at least one of the reactants sufficiently adsorbs to a monolayer and 2) the surface deposition reaction can occur with adequate growth rate and film purity. If the substrate temperature needed for the deposition reaction is too high, desorption or decomposition of the first adsorbed reactant occurs, thereby eliminating the layer-by-layer

1 process. If the temperature is too low, the deposition reaction may be
2 incomplete (i.e., very slow), not occur at all, or lead to poor film quality (e.g.,
3 high resistivity and/or high impurity content). Since the ALD process is
4 entirely thermal, selection of available precursors (i.e., reactants) that fit the
5 temperature window becomes difficult and sometimes unattainable. Due to
6 the above-mentioned temperature related problems, ALD has been typically
7 limited to the deposition of semiconductors and insulators as opposed to
8 metals. ALD of metals has been confined to the use of metal halide
9 precursors. However, halides (e.g., Cl, F, Br) are corrosive and can create
10 reliability issues in metal interconnects.

11 Continuing with the TaN example, ALD of TaN films is confined to a
12 narrow temperature window of 400 °C to 500 °C, generally occurs with a
13 maximum deposition rate of 0.2 Å/cycle, and can contain up to several atomic
14 percent of impurities including chlorine and oxygen. Chlorine is a corrosive,
15 can attack copper, and lead to reliability concerns. The above process is
16 unsuitable for copper metallization and low-k integration due to the high
17 deposition temperature, slow deposition rate, and chlorine impurity
18 incorporation.

19 In conventional ALD of metal films, gaseous hydrogen (H₂) or
20 elemental zinc (Zn) is often cited as the second reactant. These reactants are
21 chosen since they act as a reducing agent to bring the metal atom contained in
22 the first reactant to the desired oxidation state in order to deposit the end film.
23 Gaseous, diatomic hydrogen (H₂) is an inefficient reducing agent due to its
24 chemical stability, and elemental zinc has low volatility (e.g., it is very
25 difficult to deliver sufficient amounts of Zn vapor to the substrate) and is
26 generally incompatible with IC manufacturing. Unfortunately, due to the
27 temperature conflicts that plague the ALD method and lack of kinetically
28 favorable second reactant, serious compromises in process performance
29 result.

30 In order to address the limitations of traditional thermal or pyrolytic
31 ALD, radical enhanced atomic layer deposition (REALD, US Patent 5,916,365)

1 or plasma-enhanced atomic layer deposition has been proposed whereby a
2 downstream radio-frequency (RF) glow discharge is used to dissociate the
3 second reactant to form more reactive radical species which drives the
4 reaction at lower substrate temperatures. Using such a technique, Ta ALD
5 films have been deposited at 0.16 to 0.5 Å/cycle at 25 °C, and up to
6 approximately 1.67 Å/cycle at 250 °C to 450 °C. Although REALD results in a
7 lower operating substrate temperature than all the aforementioned
8 techniques, the process still suffers from several significant drawbacks.
9 Higher temperatures must still be used to generate appreciable deposition
10 rates. Such temperatures are still too high for some films of significant
11 interest in IC manufacturing such as polymer-based low-k dielectrics that are
12 stable up to temperatures of only 200 °C or less. REALD remains a thermal or
13 pyrolytic process similar to ALD and even CVD since the substrate
14 temperature provides the required activation energy for the process and is
15 therefore the primary control means for driving the deposition reaction.

16 In addition, Ta films deposited using REALD still contain chlorine as
17 well as oxygen impurities, and are of low density. A low density or porous
18 film leads to a poor barrier against copper diffusion since copper atoms and
19 ions have more pathways to traverse the barrier material. Moreover, a porous
20 or under-dense film has lower chemical stability and can react undesirably
21 with overlying or underlying films, or with exposure to gases commonly used
22 in IC manufacturing processes.

23 Another limitation of REALD is that the radical generation and
24 delivery is inefficient and undesirable. RF plasma generation of radicals used
25 as the second reactant such as atomic H is not as efficient as microwave
26 plasma due to the enhanced efficiency of microwave energy transfer to
27 electrons used to sustain and dissociate reactants introduced in the plasma.
28 Furthermore, having a downstream configuration whereby the radical
29 generating plasma is contained in a separate vessel located remotely from the
30 main chamber where the substrate is situated and using a small aperture to
31 introduce the radicals from the remote plasma vessel to the main chamber

1 body significantly decreases the efficiency of transport of the second radical
2 reactant. Both gas-phase and wall recombination will reduce the flux of
3 desired radicals that can reach the substrate. In the case of atomic H, these
4 recombination pathways will lead to the formation of diatomic H₂, a far less
5 effective reducing agent. If the plasma used to generate the radicals was
6 placed directly over the substrate, then the deposition of unwanted impurities
7 and particles can occur similarly to the case of plasma-assisted CVD.

8 Finally, ALD (or any derivative such as REALD) is fundamentally slow
9 since it relies on a sequential process whereby each deposition cycle is
10 comprised of at least two separate reactant flow and evacuation steps, which
11 can occur on the order of minutes with conventional valve and chamber
12 technology. Significant improvements resulting in faster ALD are needed to
13 make it more suitable for commercial IC manufacturing.

Brief Description of The Drawings

1 Figure 1 is a schematic of a deposition system suitable for modulated
2 ion-induced atomic layer deposition (MII-ALD).

3 Figure 2A depicts a timing sequence for an improved ALD method
4 incorporating periodic exposure of the substrate to ions.

5 Figure 2B is another timing sequence for an improved ALD method
6 incorporating periodic exposure of the substrate to ions.

7 Figure 3A shows the MII-ALD method utilizing ion flux modulation to
8 vary the substrate exposure to ions.

9 Figure 3B shows the timing of the MII-ALD method utilizing ion
10 energy modulation to vary the substrate exposure to ions by varying the
11 substrate bias.

12 Figures 4A-F show methods of modulating the MII-ALD process.

13 Figure 5 shows an electrostatic chuck (ESC) system suitable for
14 modulating the ion energy in the MII-ALD process: a) in topological form;
15 and, b) as an equivalent electrical circuit.

Summary and Detailed Description of the Invention

1 The present invention relates to methods and apparatuses useable for
2 the deposition of conformal solid thin films of one or more elements at low
3 temperature. More particularly, the present invention relates to an enhanced
4 sequential or, more preferably, non-sequential atomic layer deposition
5 apparatus and technique suitable for deposition of barrier layers, adhesion
6 layers, seed layers, and low dielectric constant (low-k) films, high dielectric
7 constant (high-k) films, and other conductive, semi-conductive, and non-
8 conductive thin films.

9 More specifically, the present invention resolves the previously
10 presented problems encountered in the prior art (e.g., REALD) by 1)
11 providing a non-thermal or non-pyrolytic means of triggering the deposition
12 reaction; 2) providing a means of depositing a purer film of higher density at
13 lower temperatures; 3) providing a faster and more efficient means of
14 modulating the deposition sequence and hence the overall process rate
15 resulting in an improved deposition method; and, 4) providing a means of
16 improved radical generation and delivery.

17 Improvements to ALD processing, e.g., the REALD mentioned
18 previously, remain "thermal" or "pyrolytic" processes since the substrate
19 temperature provides the required activation energy and is the primary
20 control knob for driving the deposition reaction. Alternatively, we propose a
21 novel approach by providing the required activation energy from a "non-
22 thermal" source. In particular, we propose driving the deposition reaction
23 primarily via substrate exposure to impinging ions wherein the ions are used
24 to deliver the necessary activation energy to the near surface atoms and
25 adsorbed reactant(s) via collision cascades.

26 Conventional deposition processes used in the semiconductor industry
27 (including ALD) typically deposit materials at temperatures in the range of
28 300-600 °C. The deposition method described herein can be effected at much
29 lower temperatures, in practice as low as 25 °C or below. Note that this
30 process is ion-triggered (i.e., ion-induced) as opposed to ion-assisted in that

1 deposition will not generally occur without ion bombardment since ions are
2 used as the primary means of providing the activation energy required for
3 deposition. A primary benefit of ion-induced processing is the deposition of
4 higher density films of superior purity and adhesion properties. This result
5 occurs due to ion bombardment induced densification.

6 Figure 1 illustrates a deposition system suitable for modulated ion-
7 induced atomic layer deposition (MII-ALD). The invention described herein
8 also incorporates a means of modulating the exposure of the substrate to ions.
9 By modulating 1) the ion flux; 2) the energy of the ions striking the substrate;
10 or a combination of (1) and (2), the deposition reaction can be precisely
11 toggled "on" or "off". If the ion flux or energy is at a "low" state, then no
12 deposition results or deposition occurs so slowly that essentially no
13 deposition results. If the impinging ion flux or energy is at a "high" state,
14 then deposition occurs. Since the substrate (which may be a "bare" substrate,
15 e.g., a silicon wafer before any films have been deposited, or it may be a
16 substrate which may already have had one or more films deposited on its
17 surface) 181 is preferably maintained at a low substrate temperature, the first
18 and second reactants do not thermally react with any appreciable rate or do
19 not react at all. Instead, the deposition reaction only takes place when either
20 the ion flux or ion energy is toggled to a suitable "high state". The desired
21 film thickness is built up by repeating the ion pulses (either of flux or energy)
22 the required number of cycles. Furthermore, since modulation of the ion flux
23 or ion energy can occur on a much faster time scale (KHz range) than the
24 conventional valve and pump technology used in ALD (up to minutes per
25 cycle), this deposition method is more suitable for commercial IC
26 manufacturing. This method shall be referred to herein as modulated ion-
27 induced atomic layer deposition (MII-ALD).

28 In addition, the present invention also improves upon the prior art by
29 employing a microwave generated plasma 172 substantially contained in the
30 main chamber body 190 that is isolated via a distribution showerhead 171
31 comprised of a series or array of apertures 173 which resolves the issues of

1 radical generation and delivery, while preventing gas-phase precursor
2 cracking (i.e., fragmentation or breaking down the precursor gas into its
3 constituent elements) and impurity and/or particle generation directly above
4 the wafer 181. The plasma is contained within the plasma source chamber 170
5 itself and is not in direct communication with the substrate 181. In MII-ALD,
6 the same plasma is used to generate both ions 177 (used to drive the surface
7 reactions) and radicals 176 (used as the second reactant), but is isolated from
8 the first reactant 100 which typically contains both the principal element(s)
9 desired in the end film, but also unwanted impurity containing byproducts.
10 Therefore, primarily only the radicals 176 and ions 177 are able to travel
11 through the showerhead apertures 175. The plasma 172 is essentially
12 contained within the plasma source chamber and does not intermingle with
13 the precursor gases 100, 120.

14 The present invention utilizes ion imparted kinetic energy transfer
15 rather than thermal energy (e.g., REALD, ALD, PECVD, CVD, etc.) to drive
16 the deposition reaction. Since temperature can be used as a secondary control
17 variable, with this enhancement films can be deposited using MII-ALD at
18 arbitrarily low substrate temperatures (generally less than 350 °C). In
19 particular, films can be deposited at or near room temperature (i.e., 25°C) or
20 below.

21 The system of Figure 1 contains a substantially enclosed plasma source
22 chamber 170 located in substantial communication with or, more preferably,
23 substantially within a main chamber body 190. The plasma 172 is used to
24 dissociate feed gases 130, 110 to generate both ions 177 and radicals 176.
25 Typical feed gases 130 used for ion generation include, but are not restricted
26 to Ar, Kr, Ne, and Xe. Typical feed gases 110 (e.g., precursor B) used for
27 radical generation include, but are not restricted to H₂, O₂, N₂, NH₃, and H₂O
28 vapor. The ions 177 are used to deliver the energy needed to drive surface
29 reactions between the first adsorbed reactant and the generated radicals 176.
30 Inductively coupled RF (e.g., 400 KHz, 2 MHz, 13.56 MHz, etc.) power 160 can
31 be used to generate the plasma via solenoidal coils located within or outside

1 of the plasma chamber (not shown in Figure 1). More preferably, microwave
2 (e.g., generally 2.45 GHz or higher frequencies) power 160 is coupled to the
3 plasma source chamber 170 via a suitable means such as a waveguide or
4 coaxial cable. Microwave energy can be more efficiently transferred to
5 ionizing electrons, leading to higher ionization fractions. This is of particular
6 importance in the generation of radicals 176 (i.e., a chemical fragment of a
7 larger molecule) such as atomic hydrogen, or any of a number of other
8 reactive groups such as nitrogen atoms (N), oxygen atoms (O), OH molecules,
9 or NH molecules, or a combination thereof. These radicals serve as the
10 second reactant. Microwave or radio-frequency (RF) power 160 is coupled to
11 the plasma 172 via a dielectric material 173, which may be a dielectric window
12 such as quartz embedded in the chamber wall, or it may be empty space in
13 the case of a microwave or RF antenna located within the plasma chamber.

14 In addition, a distribution showerhead 171, containing a series or array
15 of apertures 175 through which ions 177 and radicals 176 are delivered to the
16 substrate 181, isolates the main process chamber 180 from the plasma source
17 chamber 170. A pressure drop (for example, a 5 or 10 times decrease in
18 pressure, with the main processing chamber 180 being at the lower pressure)
19 is thereby created between the plasma source chamber 170 and the main
20 processing chamber 180 to project the ions 177 and radicals 176 to the
21 substrate 181 via the distribution showerhead 171. The plasma source
22 chamber 170 is generally of comparable diameter to the main chamber body
23 190 to enable large area exposure of the sample. The size, aspect ratio, and
24 distribution of the showerhead apertures 175 can be optimized to provide
25 uniform exposure of the substrate 181 and the desired ion 177 to radical 176
26 ratio. The distance between this showerhead 171 and the substrate 181 may
27 vary depending on the application. For the processing of wafers in the IC
28 industry, this distance is preferably at most two wafer diameters and more
29 preferably less than or equal to one half a wafer diameter.

30 Having a substantially enclosed plasma generation chamber 170
31 situated within the main chamber 190 allows efficient and uniform delivery of

ions 177 and radicals 176 to the substrate 181. In addition, by isolating the plasma 172 from the main chamber 180 prevents gas-phase cracking of the first reactant 100 (e.g., precursor A), which is introduced directly to the main processing chamber 180 via a gas distribution manifold 199. Precursor A 100 may be any one or more of a series of gaseous compounds used for depositing semiconductors, insulators, metals or the like that are well-known in the art (e.g., PDEAT (pentakis(diethylamido)tantalum), PEMAT (pentakis(ethylmethylamido)tantalum), TaBr₅, TaCl₅, TBTDET (t-butylimino tris(diethylamino) tantalum), TiCl₄, TDMAT (tetrakis(dimethylamido)titanium), TDEAT (tetrakis(diethylamino)titanium), CuCl, Cupraselect® ((Trimethylvinylsilyl)hexafluoroacetylacetonato Copper I), W(CO)₆, WF₆, etc.) and examples will be further discussed herein. Finally, the ion/radical distribution showerhead 171 shields the dielectric wall 173 adjacent to the supplied RF or microwave power 160 against being coated by precursor A 100 during processing which can degrade power transfer to the plasma 172 in processing systems found in the prior art. This is of particular importance in the case of deposition of conductors whereby if the dielectric 173 is fully exposed to the metal containing first reactant 100 (e.g., precursor A) and if the plasma 172 was directly generated within the main chamber 190 without the use of an isolating distribution showerhead 171, then metal deposition onto the dielectric 173 will eventually shield out RF or microwave power 160 from the plasma 172 such that the plasma 172 will extinguish.

Figure 2A depicts a sequence for an improved ALD method incorporating periodic exposure of the substrate to ions. In this variant of the method, ion exposure 230 begins with the introduction of the second precursor 220 (especially when plasma generated radicals 176 are used as the second precursor or reactant). This figure illustrates one embodiment of MII-ALD utilizing the apparatus described in Figure 1. This results in an enhanced sequential ALD process as follows:

1) First exposure 200: The substrate 181 is exposed to a first gaseous reactant 100 (e.g., precursor A), allowing a monolayer of the reactant to form

1 on the surface. The substrate 181 may be at any temperature below the
2 decomposition temperature of the first gaseous reactant although it is
3 preferable for the temperature to generally be less than approximately 350 °C.

4 2) First evacuation 210: The excess reactant 100 is removed by
5 evacuating 214 the chamber 180 with a vacuum pump 184.

6 3) Second exposure 220: Unlike conventional ALD, the substrate 181 is
7 simultaneously exposed to ions 177 and a second gaseous reactant (e.g.,
8 microwave or RF plasma generated radicals 176) during this step with the
9 substrate 181 (e.g., wafer) biased to a negative potential V_{bias} 185. Microwave
10 or RF power 160 is supplied into the plasma chamber 170 to generate both the
11 ions 177 (e.g., argon-ion (Ar^+)) and radicals 176 (e.g., H atoms). The ions will
12 strike the wafer 181 with an energy approximately equal to $(e|V_{bias}| + e|V_p|)$
13 where V_p is the plasma 172 potential (typically 10V to 20V). V_{bias} (-20V to -
14 500V) is typically chosen to be greater than V_p in magnitude, and is used to
15 control the ion 177 energy. With the activation energy now primarily
16 supplied by ions 177 instead of thermal energy, the first and second (chemi-
17 or physi-sorbed) reactants react via an ion-induced surface reaction to
18 produce a solid thin monolayer of the desired film at a reduced substrate
19 temperature below conventional ALD. The deposition reaction between the
20 first and second reactants is self-limiting in that the reaction between them
21 terminates after the initial monolayer of the first reactant 100 is consumed.

22 4) Second evacuation 210: The excess second reactant is removed by
23 again evacuating 216 the chamber 180 with the vacuum pump 184.

24 5) Repeat: The desired film thickness is built up by repeating the entire
25 process cycle (steps 1-4) many times.

26 Additional precursor gases (e.g., 120, 140) may be introduced and
27 evacuated as required for a given process to create tailored films of varying
28 compositions or materials. As an example, an optional exposure may occur in
29 the case of a compound barrier of varying composition. For example, a
30 TaN_x/Ta film stack is of interest in copper technology since TaN_x prevents
31 fluorine attack from the underlying fluorinated low-k dielectrics, whereas the

1 Ta promotes better adhesion and crystallographic orientation for the
2 overlying copper seed layer. The TaN_x film may be deposited using a
3 tantalum containing precursor (e.g., TaCl₅, PEMAT, PDEAT, TBTDET) as the
4 first reactant 100 (precursor A) and a mixture of atomic hydrogen and atomic
5 nitrogen (i.e. flowing a mixture of H₂ and N₂ into the plasma source 172) as
6 the second reactant to produce a TaN_x film. Simultaneous ion exposure is
7 used to drive the deposition reaction. Next a Ta film may be deposited in a
8 similar fashion by using atomic hydrogen (as opposed to a mixture of atomic
9 hydrogen and nitrogen) as the second reactant. An example of a tailored film
10 stack of differing materials can be the subsequent deposition of a copper layer
11 over the TaN_x /Ta bi-layer via the use of a copper containing organometallic
12 (e.g., Cu(TMVS)(hfac) or (Trimethylvinylsilyl)hexafluoroacetylacetonato
13 Copper I, also known by the trade name CupraSelect®, available from
14 Schumacher, a unit of Air Products and Chemicals, Inc., 1969 Palomar Oaks
15 Way, Carlsbad, CA 92009.) or inorganic precursor (e.g. CuCl) shown as
16 precursor C 120 in Figure 1. The copper layer can serve as the seed layer for
17 subsequent electroless or electroplating deposition.

18 A variant of the method shown in Figure 2A is illustrated in Figure 2B
19 where ion exposure is initiated after the second reactant exposure. Figure 2B
20 depicts a sequence for an improved ALD method incorporating periodic
21 exposure of the substrate 181 to ions 177. In this variant of the method, ion
22 exposure 280 begins with the evacuation 250 of the second precursor 256
23 (especially when the second precursor or reactant is not subjected to a
24 plasma). Typically, this is the case where the second precursor or reactant is
25 not a plasma-generated radical.

26 In the previous embodiments of MII-ALD, although the deposition
27 temperature can be lowered significantly, the first and second reactants are
28 still sequentially introduced into the main process chamber 180, and hence
29 will still be a slow process. It is of particular interest to eliminate or replace
30 the time-consuming flow-evacuation-flow-evacuation sequential nature of the
31 process.

1 In the preferred embodiment of the MII-ALD process, a substrate 181
2 heated (e.g., to a low temperature of less than or equal to 350 °C) or unheated
3 is simultaneously exposed to a first reactant and a second reactant, and
4 subjected to modulated ion 177 exposure. By modulating 1) the ion flux (i.e.
5 the number of ions hitting the substrate per unit area per unit time); 2) the
6 energy of the ions striking the substrate; or a combination of (1) and (2), the
7 deposition reaction can be precisely toggled "on" or "off". Since the substrate
8 181 is preferably maintained at a low substrate temperature, the first and
9 second reactants do not thermally react with any appreciable rate or do not
10 react at all when the ion flux or energy is toggled to a "low" state. Instead,
11 the deposition reaction only takes place when either the ion flux or ion energy
12 is toggled to a suitable "high state". Ion flux or energy modulation can vary
13 generally from 0.1 Hz to 20 MHz, preferably from 0.01 KHz to 10 KHz.
14 During deposition, the main process chamber 180 pressure can be maintained
15 in the range of generally 10^2 to 10^{-7} torr, more preferably from 10^1 to 10^{-4} torr,
16 depending on the chemistry involved. The desired film thickness is attained
17 via exposure of the substrate to the suitable number of modulated ion flux or
18 energy pulse cycles. This MII-ALD scheme results in a "continuous"
19 deposition process that is significantly faster than conventional sequential
20 ALD since the two, slow evacuation steps (up to minutes) are eliminated and
21 replaced by the faster (KHz range or above) ion modulation steps. The
22 modulation can be either of the ion flux via the plasma power or of the ion
23 energy via an applied periodic wafer bias.

24 The MII-ALD method utilizing ion flux modulation to control the
25 deposition cycle is illustrated conceptually in Figure 3A, with the flux
26 modulation scheme described more explicitly in Figures 4A and 4C. Figure
27 3A depicts the MII-ALD method utilizing ion flux modulation 320 to vary the
28 substrate 181 exposure to ions 177. Note that the second reactant 310, e.g.,
29 radicals, is synchronized with the ion flux via 320 plasma power modulation,
30 causing a periodic exposure of the substrate to ions and radicals. Varying the
31 power 160 delivered to the plasma 172 can vary the ion flux from little or

1 none to maximum ion production. Plasma power modulation can take the
2 form of variations in frequency (periodicity), magnitude, and duty-cycle.
3 Increasing plasma power 160 leads to increasing plasma 172, and hence,
4 increased ion 177 density. Since the deposition process is ion-induced, having
5 little or no ion bombardment will essentially stop the deposition process,
6 whereas increased ion bombardment will cause deposition to occur. A
7 constant wafer bias 185 (DC in Figure 4C or RF in Figure 4A) is applied to
8 define the ion energy of the modulated ion flux in this embodiment and is
9 chosen to be sufficiently high so that ion-induced surface reactions can occur.
10 Note that in this embodiment since the plasma (either RF or preferably
11 microwave) power 160 is used to generate both ions 177 and radicals 176, the
12 second reactant (e.g., radicals) flux 310 is synchronized with the ion flux 320
13 pulses. The radical feed gas 110 (H_2 for example) flow, however, does not
14 change. Instead, the radical flux 310 (e.g., fraction of H_2 which is converted to
15 atomic H) is modulated.

16 Alternatively, subjecting the substrate 181 to a non-constant wafer
17 voltage bias 185 can vary the incoming ion energy at a fixed plasma power
18 160 (i.e., ion flux). This preferred embodiment of MII-ALD is illustrated
19 conceptually in Figures 3B, and more explicitly in Figures 4B and 4D. Figure
20 3B shows the MII-ALD method utilizing ion energy modulation 350 to vary
21 the substrate 181 exposure to ions 177 by varying the substrate bias 185. The
22 applied bias 185 can take the form of variations in frequency (periodicity),
23 magnitude, and duty-cycle. A DC as shown in Figure 4D or RF (e.g., 400
24 kHz, 2 MHz, 13.56 MHz, etc.) as shown in Figure 4B power supply can be
25 used. When the wafer potential is "low" (e.g., near or at zero with respect to
26 ground), the incoming ions 177 do not have enough energy to induce surface
27 deposition reactions. When the wafer 181 potential is "high" (e.g., at a
28 significant negative potential relative to ground), the incoming ions 177 will
29 have the necessary energy to induce surface deposition reactions via collision
30 cascades. In such a fashion, the deposition can be turned "on" or "off" by
31 modulating the wafer bias voltage 185, and hence the impinging ion 177

1 energy. Typical wafer voltages can range from generally -20 V to -1000 V,
2 but preferably in the -25 V to -500 V range, and more preferably in the -50 V
3 to -350 V range during deposition. The bias voltage 185 is coupled to the
4 wafer via the pedestal 182. Preferably, the substrate pedestal 182 is an
5 electrostatic chuck (ESC) to provide efficient coupling of bias voltage to the
6 substrate. The ESC is situated in the main processing chamber 180 and can be
7 cooled via a fluid coolant (preferably a liquid coolant) and/or heated (e.g.,
8 resistively) to manipulate the substrate temperature.

9 As illustrated in Figure 5 for the case of an applied DC bias, the
10 preferred electrostatic chuck is a "coulombic" ESC 500 (bulk resistivity
11 generally greater than 10^{13} ohm-cm) rather than one whose bulk material
12 effects are dominated by the Johnson-Rahbek (JR) effect (bulk resistivity
13 between 10^8 and 10^{12} ohm-cm). Typically, the substrate potential is a complex
14 function of the voltage of the electrostatic "chucking" electrodes if these
15 voltages are established relative to a reference potential, but is simplified in
16 the case of "coulombic" (non-JR) ESC. However, if the power supply 510 that
17 powers the ESC 500 is truly floating, i.e., the entire system has a high
18 impedance to the chamber 180 potential (usually ground) including the
19 means of supplying power, then the substrate potential can be arbitrary. In
20 particular, if the ESC power supply 510 is also center-tapped 518, then the
21 wafer potential can be established by connecting the center tap 518 to the
22 output of a power amplifier 520. This power amplifier can be controlled by a
23 computer or a waveform generator 530 to periodically drop the substrate
24 potential to a negative value for a certain period of time. It is desired to have
25 independent control of the magnitude, frequency (periodicity), and duty cycle
26 of this substrate bias pulse train. Such an ESC system is depicted in Figure 5,
27 which shows an ESC system suitable for modulating the ion energy in the
28 MII-ALD process: a) in topological form; and, b) as an equivalent electrical
29 circuit.

30 The deposition rate is affected by the choice of the critical bias pulse
31 train variables: the magnitude, frequency (periodicity), and duty cycle.

1 Preferably, when the bias frequency is high (e.g., 100 Hz-10 KHz) with a short
2 duty cycle (e.g., less than 30%), reducing the net, time-averaged current
3 (which can cause substrate potential drift, de-chucking problems, or charge-
4 induced device damage) while providing a charge relaxation period wherein
5 the ion charges accumulated during ion exposure can redistribute and
6 neutralize.

7 Once the deposition rate is calibrated for a particular recipe
8 (Angstroms/cycle), the ability to accurately determine the film thickness by
9 counting cycles is a further benefit of this modulation scheme. The higher the
10 frequency, the finer the resolution of this critical deposition process
11 performance metric.

12 Alternatively, the substrate potential can be modulated by imparting
13 an induced DC bias to the substrate by applying RF power to the pedestal.
14 Preferably, the RF power is coupled into the ESC electrodes. Figures 4A-F
15 illustrate the preferred methods of modulating the MII-ALD process. In
16 Figure 4A, an RF bias power B_2 is applied to the substrate pedestal 182
17 imparting an induced DC bias V_2 to the substrate while the plasma (either
18 microwave or RF) power 400 is varied periodically between a high P_1 and a
19 low P_2 power state. In Figure 4B, plasma (either microwave or RF) power 410
20 is constant P_1 while an RF bias power, applied to the substrate pedestal 182, is
21 varied between a low B_1 and a high B_2 bias state (V_1 and V_2 are the DC offset
22 or bias voltages resulting from the applied RF bias power). In Figure 4C, a
23 negative DC bias 425 is applied to the substrate pedestal 182 while the plasma
24 (either microwave or RF) power 420 is varied periodically between a high P_1
25 and a low power P_2 state. In Figure 4D, plasma (either microwave or RF)
26 power is constant 430 while a DC bias 435 applied to the substrate pedestal
27 182 is varied between a zero V_1 and a negative voltage state V_2 . In Figure 4E,
28 a mechanical shutter periodically occludes the ion source. All the while, the
29 plasma power 440 (either microwave or RF) and substrate voltage 445 are
30 held constant. In Figure 4F, a source area that is smaller than the substrate
31 181 is preferably used. In this case, plasma (either microwave or RF) power

1 450 is constant, a negative DC substrate bias 455 is constant, and the source
2 and substrate 181 are moved relative to each other 457, exposing only a
3 portion of the substrate 181 at a time. The methods proposed in Figure 4B
4 and Figure 4D, whereby the substrate bias is modulated at a constant plasma
5 power 410, 430 and hence ion flux, are most preferred.

6 MII-ALD can be used to deposit dielectric, semiconducting, or metal
7 films, among others, used in the semiconductor, data storage, flat panel
8 display, and allied as well as other industries. In particular, the method and
9 apparatus is suitable for the deposition of barrier layers, adhesion layers, seed
10 layers, low dielectric constant (low-k) films, and high dielectric constant
11 (high-k) films.

12 This process utilizes independent control over the three constituents of
13 plasma - ions, atoms, and precursors. Decoupling these constituents offer
14 improved control over the deposition process.

15 An added benefit of using MII-ALD is that with proper choice of the
16 second reactant, selective ion-enhanced etching and removal of unwanted
17 impurities can be performed. As an example, for many chemistries, the
18 preferred second reactant is monatomic hydrogen (H) 176. Simultaneous
19 energetic ion and reactive atomic H bombardment will cause selective
20 removal of unwanted impurities (e.g., containing carbon, oxygen, fluorine, or
21 chlorine) commonly associated with organometallic precursors (e.g., TBTDET,
22 PEMAT, PDEAT, TDMAT, TDEAT), and proceed with removal rates superior
23 to either chemical reaction (e.g., atomic H only) or physical sputtering (e.g.,
24 Ar ion only) alone. Impurities lead to high film resistivities, low film density,
25 poor adhesion, and other deleterious film effects. Alternatively, in addition to
26 atomic hydrogen, other reactive groups such as nitrogen atoms (N), oxygen
27 atoms (O), OH molecules, or NH molecules, or a combination thereof may be
28 employed.

29 From the description of the preferred embodiments of the process and
30 apparatus set forth above, it is apparent to one of ordinary skill in the art that
31 variations and additions to the embodiments can be made without departing

1 from the principles of the present invention. As an example, chlorine,
2 bromine, fluorine, oxygen, nitrogen, hydrogen, other reactants and/or
3 radicals containing the aforementioned elements or a combination thereof, in
4 conjunction with energetic ion bombardment, can be used to effect etching or
5 material removal as opposed to deposition. This is of particular importance
6 in the cleaning of native oxides of copper, aluminum, silicon, and other
7 common conductor and semiconductor materials used in IC manufacturing.
8 Either the deposition or etching can be accomplished globally (as illustrated
9 in the preceding embodiments) or may be chosen to be local to a controlled
10 area (i.e., site-specific using a small, ion beam point or broad-beam source
11 scanned or otherwise stepped across the substrate, exposing only a fraction of
12 the substrate area at any given time).

Claims

What is claimed is:

1 1. A sequential method for depositing a thin film onto a substrate
2 in an evacuated chamber comprising:
3 introducing a first reactant gas into said chamber;
4 adsorption of at least one monolayer of said first reactant gas onto said
5 substrate;
6 evacuation of excess said first reactant gas from said chamber
7 introduction of at least one ion generating feed gas into said chamber;
8 generating a plasma from said ion generating feed gas to form ions;
9 exposing said substrate to said ions;
10 modulating said ions; and
11 reacting said adsorbed monolayer of said first reactant gas with said
12 ions to deposit said thin film.

1 2. The method of claim 1, wherein said ion modulation is
2 modulated in a way selected from the group consisting of modulating an ion
3 flux and modulating an ion energy.

1 3. The method of claim 1, further comprising maintaining said
2 substrate at a temperature of between about 25 °C to 350 °C.

1 4. A system for ion-induced atomic layer deposition of a film onto
2 a substrate, said system comprising:
3 a main chamber containing a plasma generation chamber for
4 generating a plasma;
5 said main chamber also containing a deposition chamber for
6 depositing said film on said substrate;
7 a distribution showerhead located between said plasma generation
8 chamber and said deposition chamber;
9 said plasma generation chamber coupled to receive at least one feed
10 gas to form said plasma for generation of ions;
11 said plasma generation chamber also coupled to receive at least one
12 feed gas to react with said plasma for generation of radicals; and
13 said deposition chamber coupled to receive at least one precursor gas
14 to react with said ions and said radicals to form said film on said substrate.

1 5. The system of claim 4, wherein said plasma generation chamber
2 is in communication with a radio frequency energy source through a
3 dielectric window.

1 6. The system of claim 5, wherein said distribution showerhead
2 shields said dielectric window from being coated by said deposition chamber
3 precursor gas.

1 7. The system of claim 4, wherein said plasma generation chamber
2 is in communication with a microwave frequency energy source.

1 8. The system of claim 4 further comprising a substrate holder
2 located in said deposition chamber, said substrate holder electrically biasing
3 said substrate via a power supply.

1 9. The system of claim 8, wherein said power supply supplies a
2 radio frequency power to induce said electrical bias on said substrate.

1 10. The system of claim 4, wherein said plasma generated in said
2 plasma generation chamber does not intermingle with said deposition
3 chamber precursor gas.

1 11. The system of claim 4, wherein said distribution showerhead is
2 comprised of one or more apertures.

1 12. The system of claim 4, wherein a deposition reaction is
2 controlled via ion-imparted kinetic energy.

1 13. The system of claim 4, further comprising a thermal heating
2 element to control said film deposition on said substrate.

1 14. A system for generating a plasma for depositing a film onto a
2 substrate, said system comprising:
3 a plasma generation source;
4 a plasma generation chamber coupled to said plasma generation
5 source;
6 a deposition chamber; and
7 a distribution showerhead separating said plasma generation chamber
8 from said deposition chamber.

1 15. The system of claim 14, wherein said plasma generation source
2 may be modulated by a change selected from a group consisting of a change
3 in frequency, a change in power magnitude, and a change in duty-cycle.

1 16. A sequential method for depositing a thin film onto a substrate
2 in an evacuated chamber comprising:
3 introducing a first reactant gas into said chamber;
4 adsorption of at least one monolayer of said first reactant gas onto said
5 substrate;
6 evacuation of excess said first reactant gas from said chamber
7 introduction of at least one ion generating feed gas into said chamber;
8 introduction of at least one radical generating feed gas into said
9 chamber;
10 generating a plasma from said ion generating feed gas and said radical
11 generating feed gas to form ions and radicals;
12 exposing said substrate to said ions and said radicals;
13 modulating said ions; and
14 reacting said adsorbed monolayer of said first reactant gas with said
15 ions and said radicals to deposit said thin film.

1 17. The method of claim 16, wherein said method is repeated until
2 the film achieves a desired thickness.

1 18. The method of claim 16, further comprising exposing said
2 substrate to at least one additional reactant gas.

1 19. The method of claim 16, wherein said substrate is
2 simultaneously exposed to said ions and said radicals

1 20. The method of claim 16, wherein said ion modulation is
2 modulated in a way selected from the group consisting of modulating an ion
3 flux and modulating an ion energy.

1 21. The method of claim 20, wherein modulation in said ion flux is
2 modulated in a way selected from the group consisting of modulating a flow
3 of said ion generating feed gas, modulating a power of said plasma,
4 modulating said exposure to said ions, and modulating the relative
5 movement between said plasma and said substrate.

1 22. The method of claim 16, further comprising maintaining said
2 substrate at a temperature of between about 25 °C to 350 °C.

1 23. The method of claim 16, further comprising inducing an
2 electrical bias on said substrate via a substrate pedestal on which said
3 substrate rests.

1 24. The method of claim 23, wherein said pedestal is an electrostatic
2 chuck (ESC) to provide coupling of said electrical bias to said substrate.

1 25. The method of claim 23, wherein said electrical bias is induced
2 by a radio frequency power supply.

1 26. The method of claim 16, wherein an energy to generate said
2 plasma is produced by a radio frequency source.

1 27. The method of claim 16, wherein an energy to generate said
2 plasma is produced by a microwave source.

1 28. A method for depositing a thin film onto a substrate in an
2 evacuated chamber comprising:
3 placing said substrate onto a substrate holder in a deposition chamber
4 area;
5 introducing at least one ion generating feed gas into a plasma
6 generation chamber area in communication with said deposition chamber
7 area, but substantially isolated via a distribution showerhead comprised of
8 one or more apertures located between said plasma generation chamber area
9 and said deposition chamber area;
10 introducing at least one radical generating feed gas into said plasma
11 generation chamber area;
12 generating a plasma from said ion generating feed gas to form ions;
13 generating a plasma from said radical generating feed gas to form
14 radicals;
15 electrically biasing said substrate to a negative potential;
16 introducing at least one reactant gas into said deposition chamber area;
17 adsorbing at least one monolayer of said reactant gas on said substrate;
18 exposing said substrate to said ions and said radicals;
19 modulating said ions; and
20 reacting said adsorbed monolayer of said reactant gas with said ions
21 and said radicals to deposit said thin film.

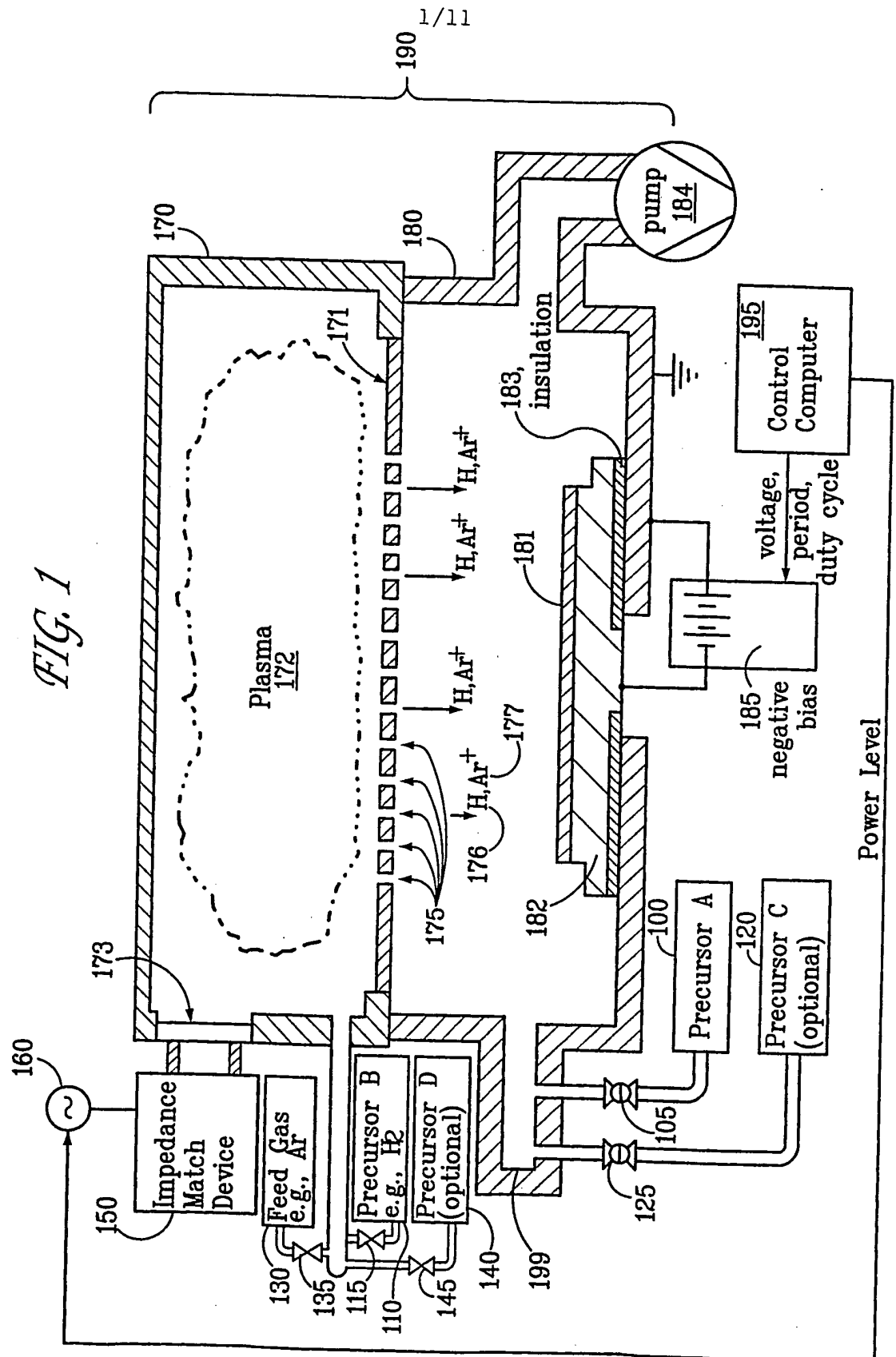
1 29. The method of claim 28, further comprising exposing said
2 substrate to at least one additional reactant gas.

1 30. The method of claim 28, further comprising exposing said
2 substrate to said reactant gas while varying exposure of said substrate to said
3 ions via said ion modulation.

1 31. The method of claim 30, wherein said ion modulation is effected
2 in a way selected from the group consisting of modulating an ion flux and
3 modulating an ion energy.

1 32. The method of claim 31, wherein modulation in said ion flux is
2 modulated in a way selected from the group consisting of modulating a flow
3 of said ion generating feed gas, modulating a power of said plasma,
4 mechanically occluding said ions, and modulating the relative movement
5 between said plasma and said substrate.

1 33. The method of claim 28, further comprising maintaining said
2 substrate at a temperature of between about 25 °C to 350 °C.



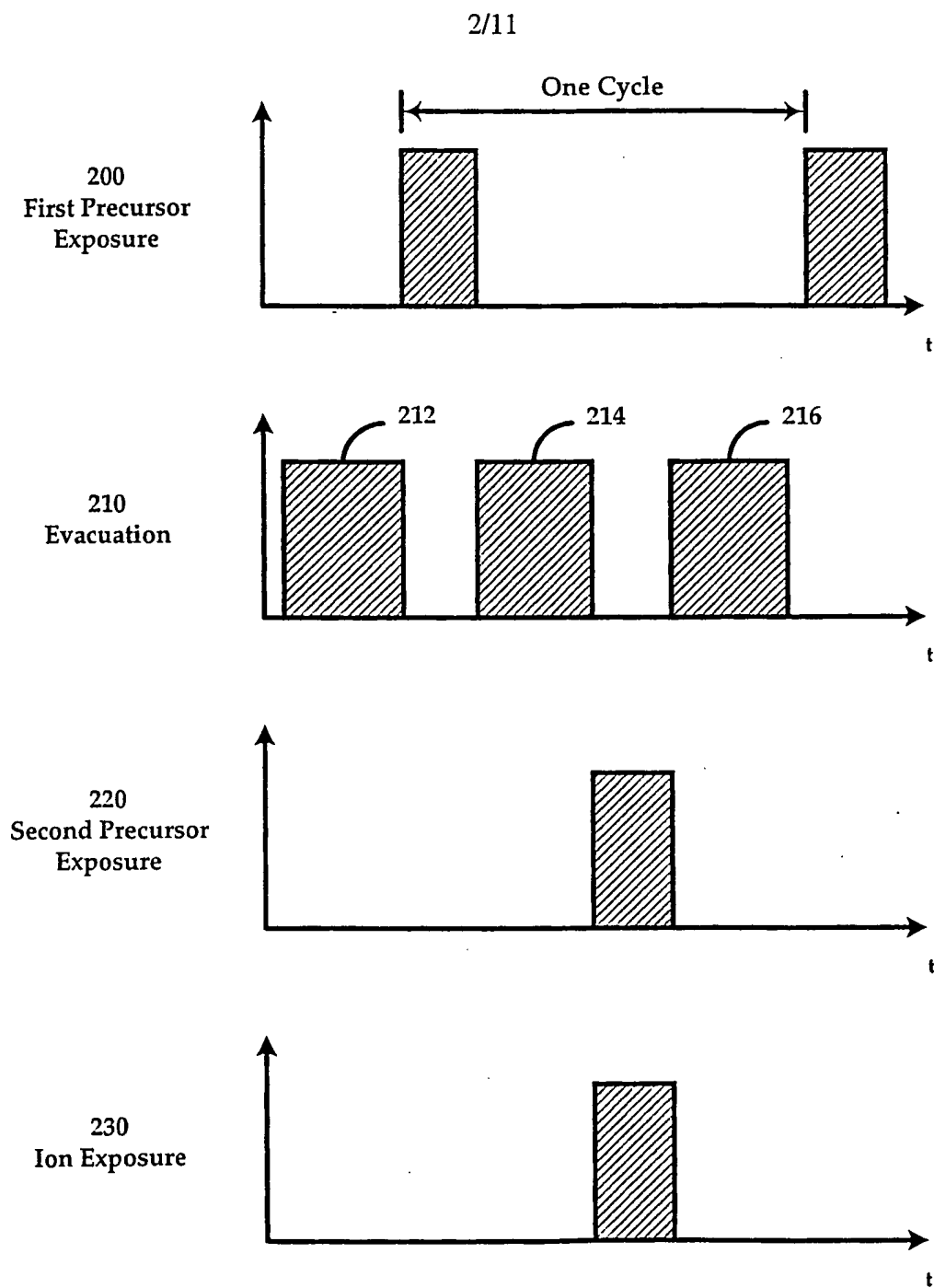


Figure 2A

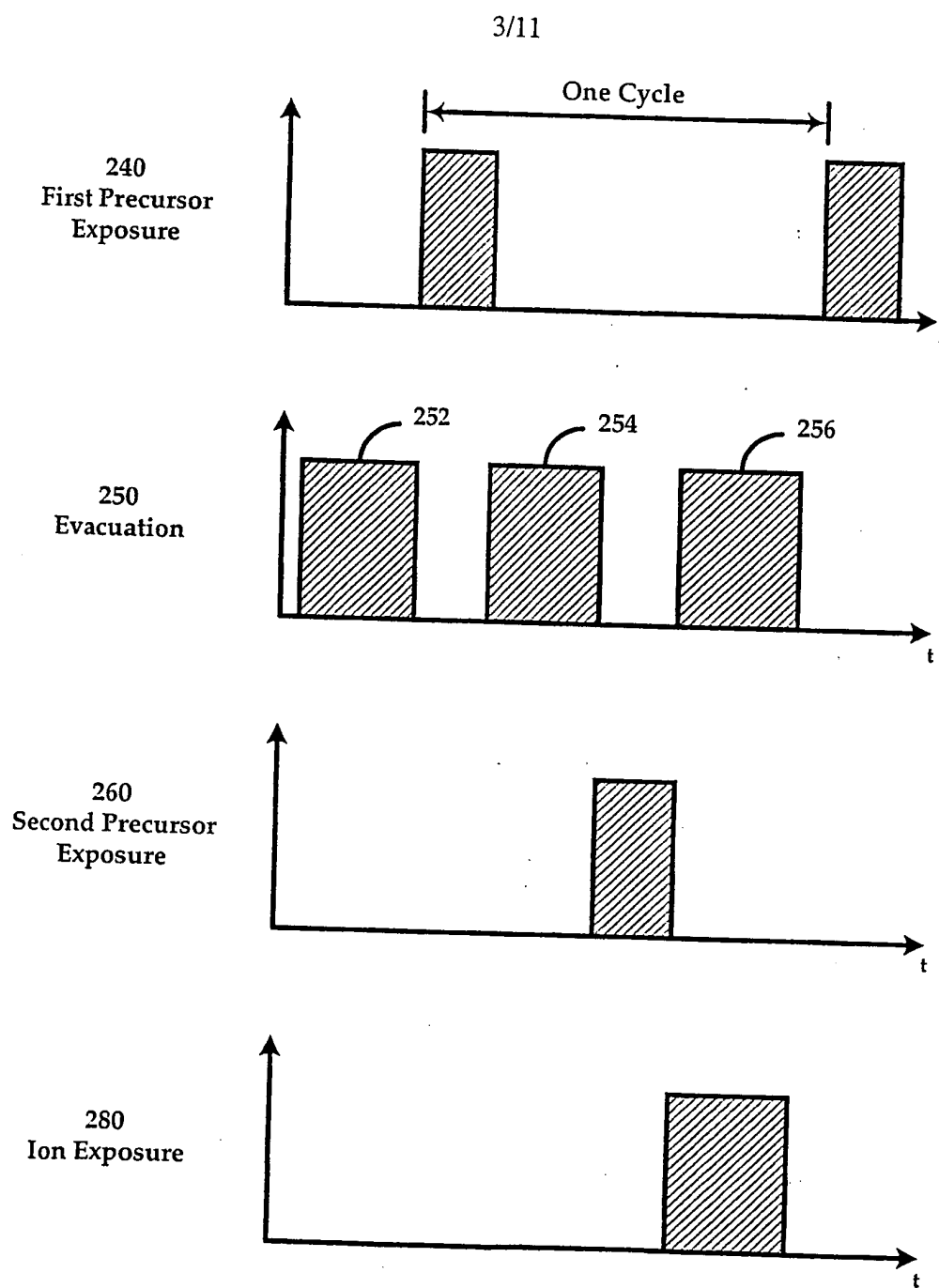
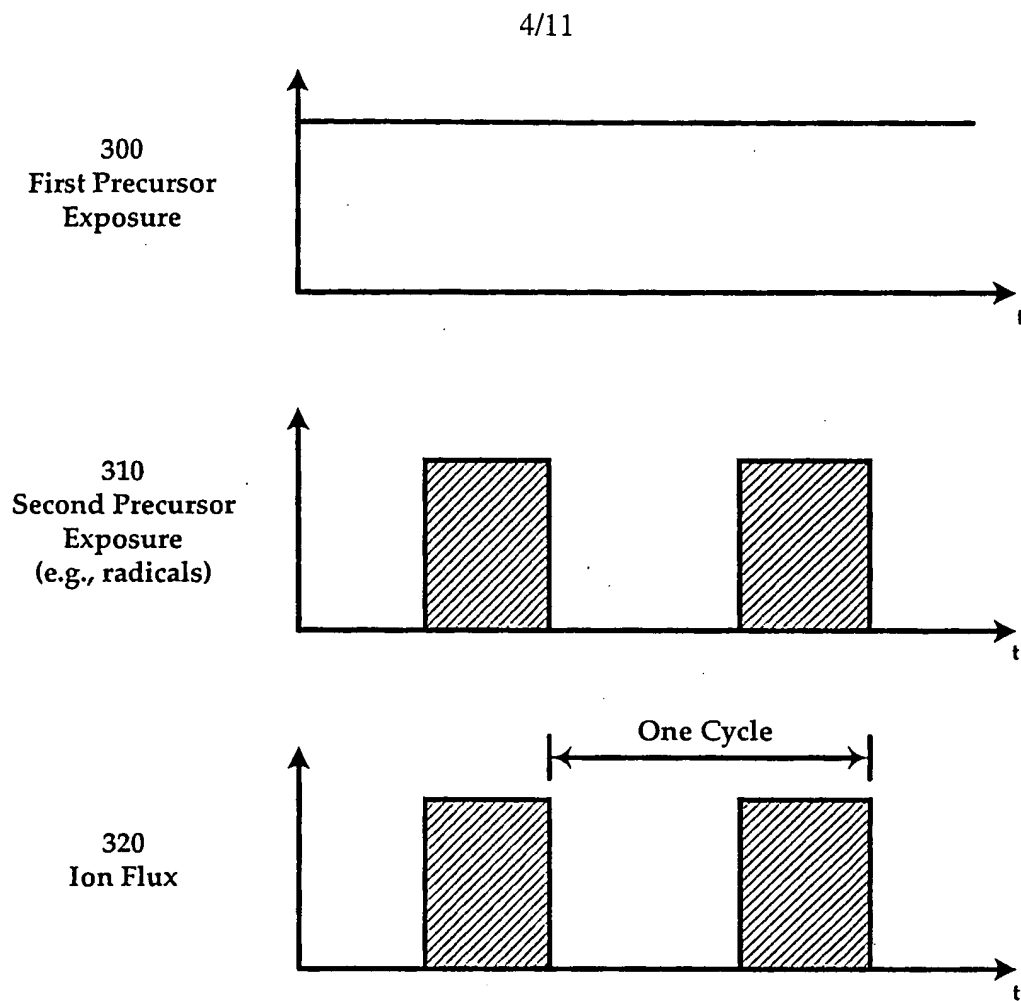
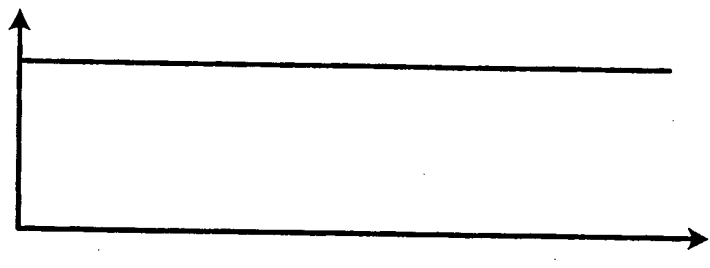


Figure 2B

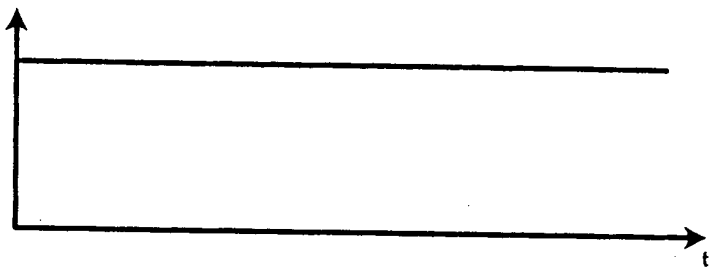
**Figure 3A**

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330
First Precursor
Exposure



340
Second Precursor
Exposure
(e.g., radicals)



350
Ion Energy

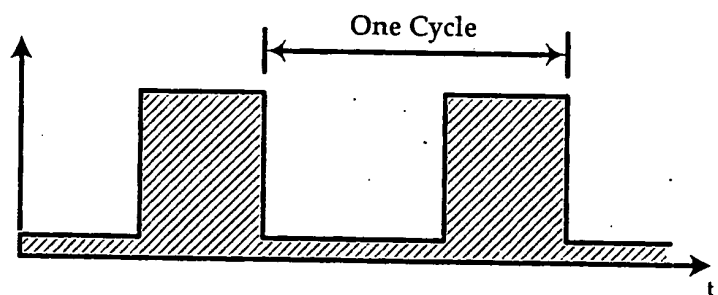


Figure 3B

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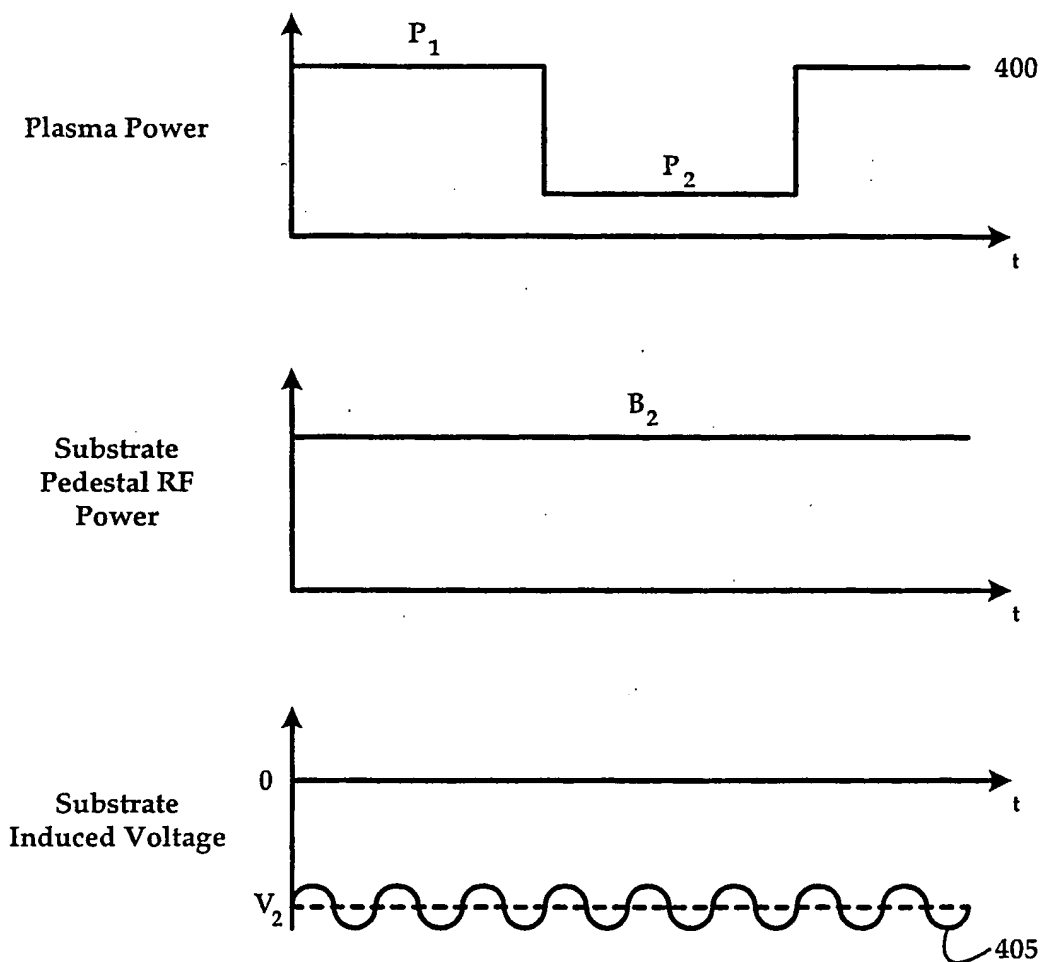


Figure 4A

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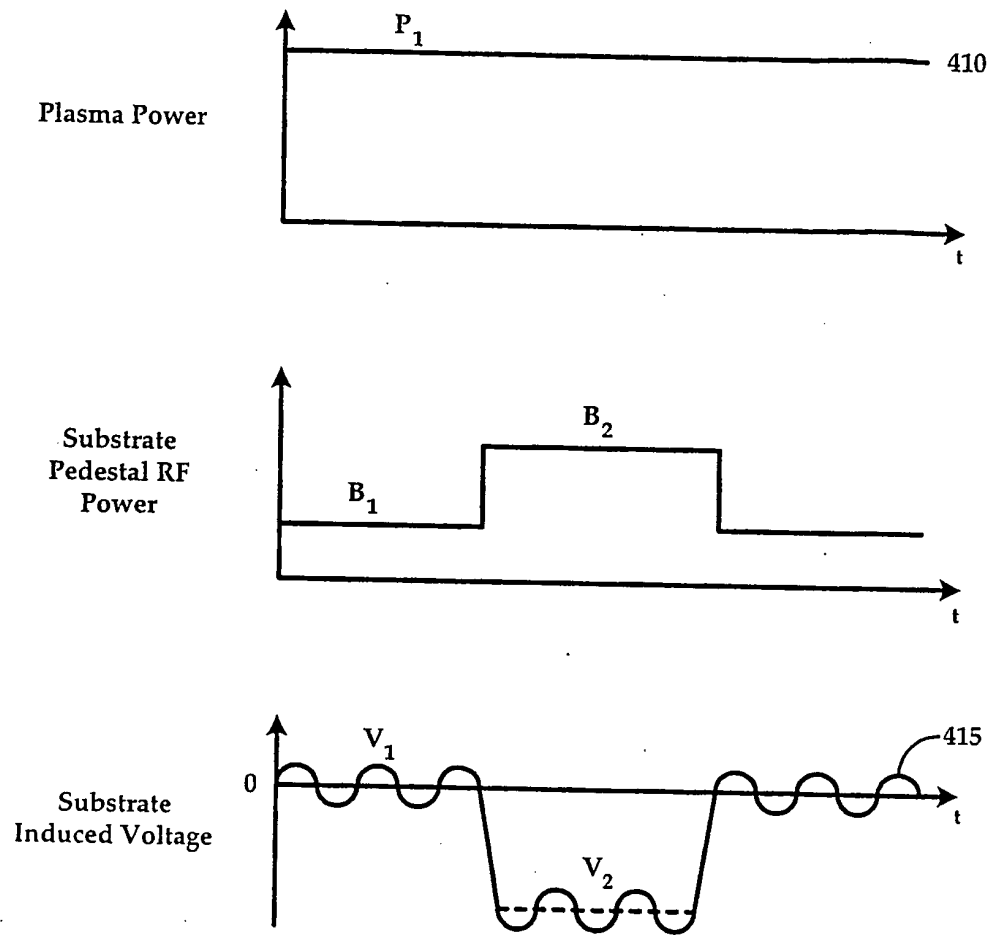


Figure 4B

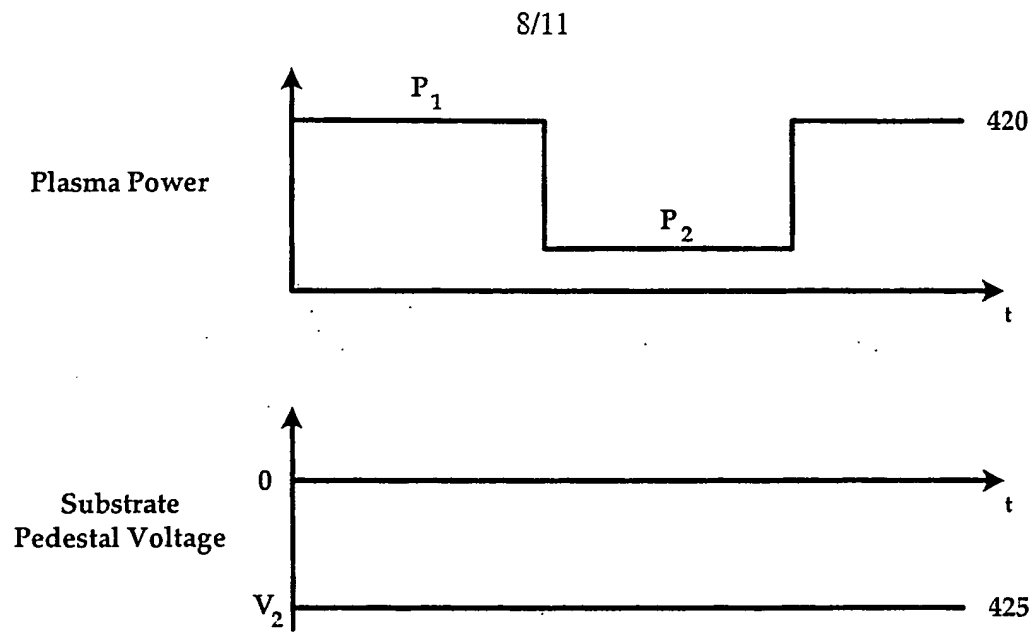


Figure 4C

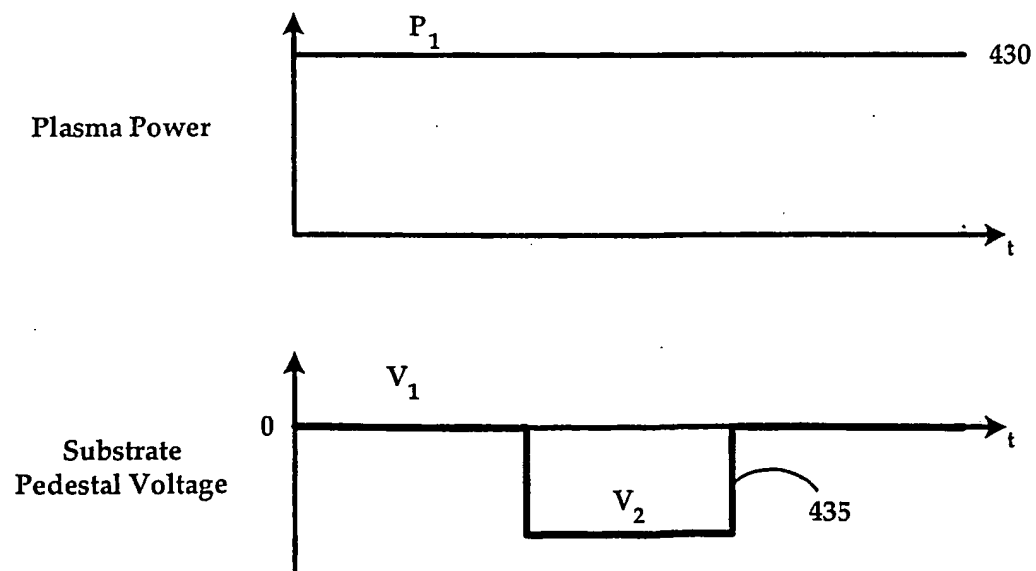


Figure 4D

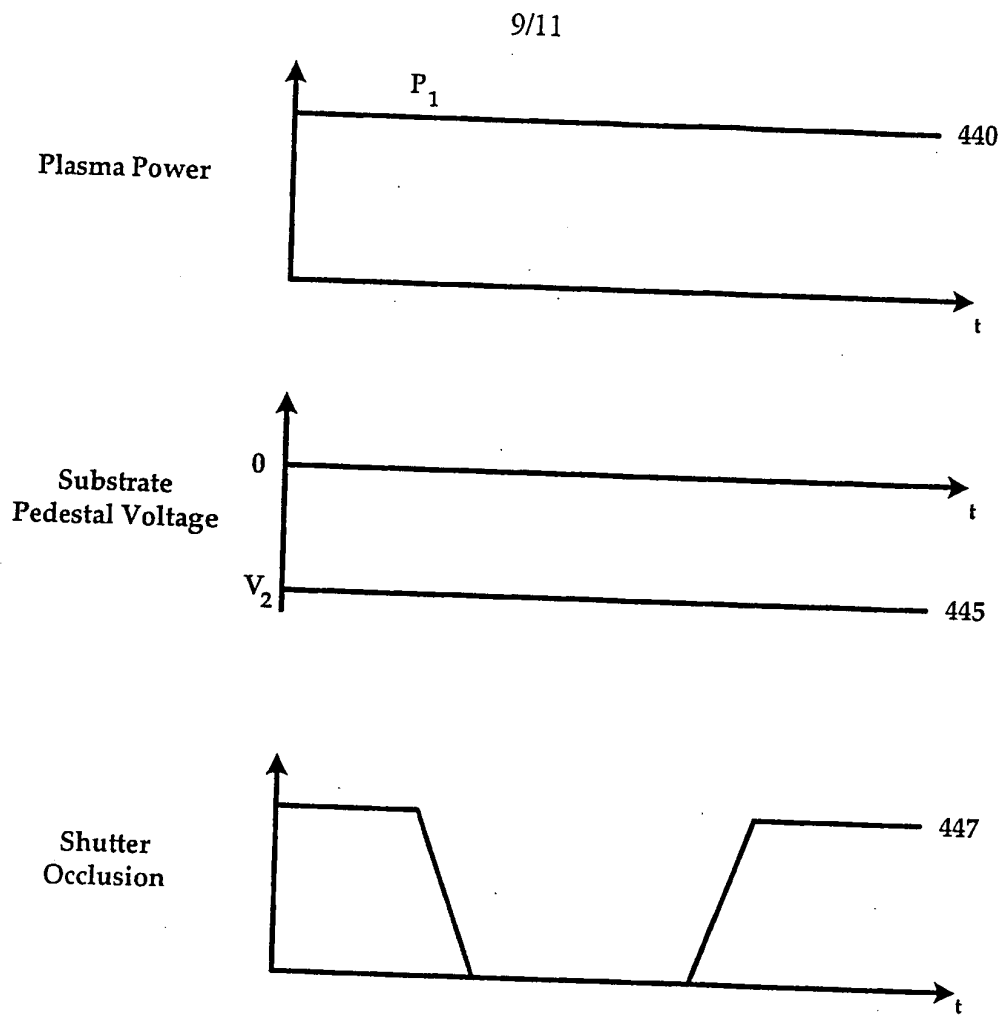


Figure 4E

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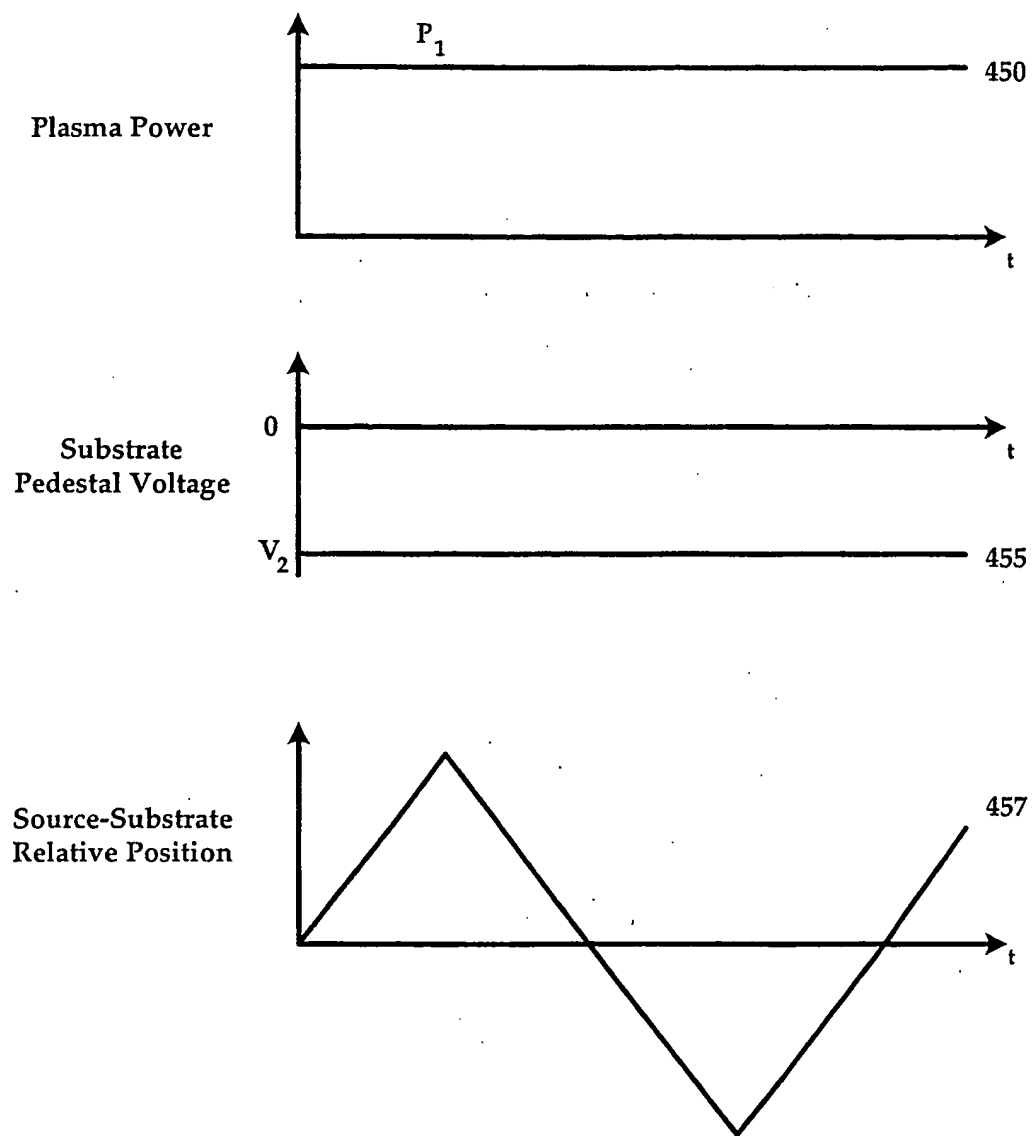


Figure 4F

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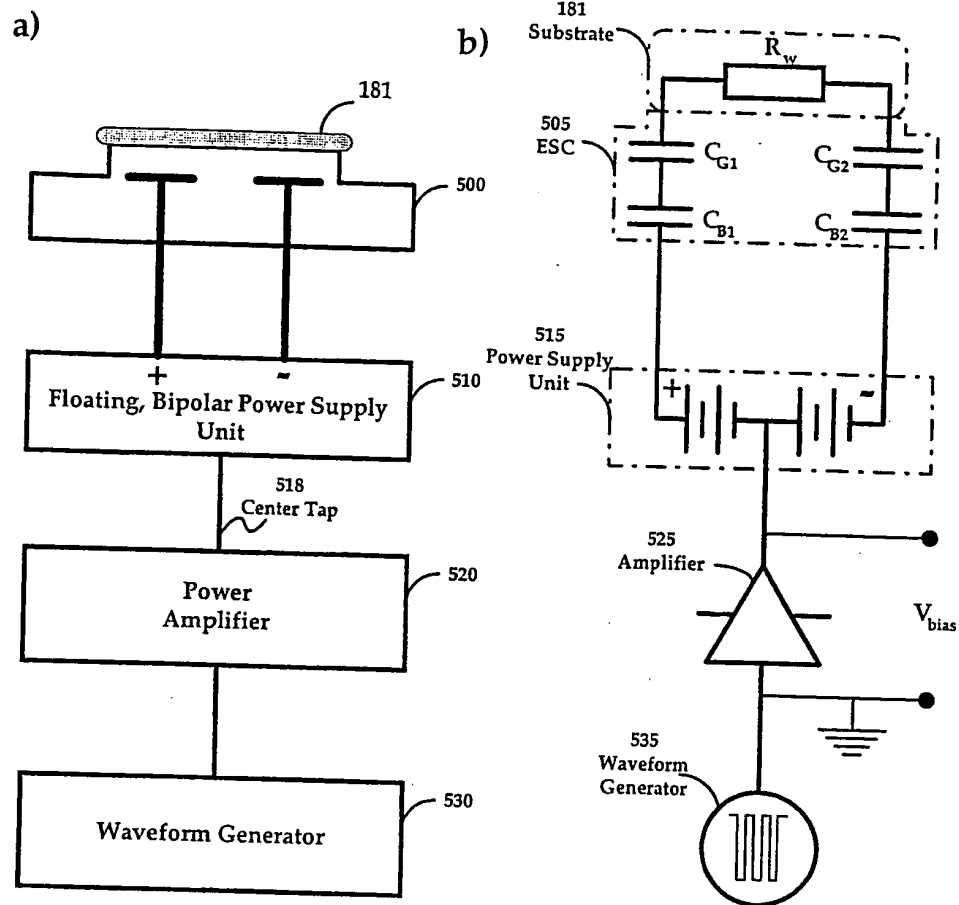


Figure
5

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US01/50350

A. CLASSIFICATION OF SUBJECT MATTER IPC(7) : B05D 3/04; C23C 16/00, 16/44, 16/452, 16/455, 16/505, 16/511; C30B 25/00, 25/08, 25/14; H05H 1/24 US CL : 427/561, 569, 570, 575, 248.1, 255.28, 255.5; 117/88, 92, 103, 105; 118/719, 723R, 723MW, 723I, 729 According to International Patent Classification (IPC) or to both national classification and IPC				
B. FIELDS SEARCHED Minimum documentation searched (classification system followed by classification symbols) U.S. : Please See Continuation Sheet Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched none Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) Please See Continuation Sheet				
C. DOCUMENTS CONSIDERED TO BE RELEVANT				
Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.		
X --- Y	US 5,916,365 A (SHERMAN) 29 June 1999 (29.06.1999), abstract, figures 1-3, columns 5-6, and column 7, lines 13-26.	1-3, 16-22, 26 ----- 23-25, 27		
X,P --- Y,P	US 6,200,893 B1 (SNEH) 13 March 2001 (13.03.2001), abstract, figure 1, columns 3-6, column 7, lines 1-25, column 8, lines 5-15, column 10, lines 35-67, and column 11, lines 1-11.	1, 2, 16-21 ----- 3, 22-27		
X --- Y	US 4,401,054 A (MATSUO et al) 30 August 1983 (30.08.1983), abstract, figures 3 and 6, columns 5-7, column 8, lines 1-5, column 9, lines 39-56, column 10, lines 20-65, columns 11-12, column 14, lines 60-67, and column 15, lines 1-3 and 36-38.	4, 7-15 ----- 5, 6, 23-25		
Y	US 5,762,714 A (MOHN et al) 09 June 1998 (09.06.1998), column 2, lines 8-17.	24		
Y	US 5,478,403 A (SHINAGAWA et al) 26 December 1995 (26.12.1995), column 7, lines 20-24.	5, 6, 27		
<input type="checkbox"/> Further documents are listed in the continuation of Box C. <input type="checkbox"/> See patent family annex.				
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Date of the actual completion of the international search 11 March 2002 (11.03.2002)		Date of mailing of the international search report 04 APR 2002		
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. (703)305-3230		Authorized officer Shive Beck Telephone No. (703) 308-0661		

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US01/50350

Continuation of B. FIELDS SEARCHED Item 1:

427/532, 533, 535, 561, 562, 564, 569, 570, 573, 575, 248.1, 250, 255.23, 255.28, 255.5; 117/84, 88, 89, 91, 92, 93, 98, 99, 100, 103, 105; 118/715, 719, 723R, 723MW, 723ME, 723I, 723IR, 728, 729

Continuation of B. FIELDS SEARCHED Item 3:

WEST electronic search, all databases.

search terms: ALD, ALE, atomic layer deposition, atomic layer epitaxy, plasma, ion, radical, showerhead, sequential CVD, and various combinations thereof.